Sand and Dust Storms Compendium

Information and Guidance on Assessing and Addressing the Risks

United Nations
Convention to Combat Desertification

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Desertification

United for land

The United Nations Convention to Combat Desertification (UNCCD) is an international agreement on good land stewardship. It helps people, communities and countries create wealth, grow economies and secure enough food, clean water and energy by ensuring land users an enabling environment for sustainable land management. Through partnerships, the Convention's 197 parties set up robust systems to manage drought promptly and effectively. Good land stewardship based on sound policy and science helps integrate and accelerate achievement of the Sustainable Development Goals, builds resilience to climate change and prevents biodiversity loss.

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Secretariat of the United Nations Convention to Combat Desertification (UNCCD)
Platz der Vereinten Nationen, 53113 Bonn, Germany
Tel: +49-228 / 815-2800
Fax: +49-228 / 815-2898/99
www.unccd.int
secretariat@unccd.int

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Sand and Dust Storms Compendium

Information and Guidance on Assessing and Addressing the Risks

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Sand and Dust Storms Compendium team

Coordinator:
Utchang Kang

Co-editors:
Charles Kelly, Utchang Kang

Chapter lead authors:

Chapter 1	Charles Kelly, Utchang Kang
Chapter 2	Sara Basart
Chapter 3	Utchang Kang, Charles Kelly
Chapter 4	Charles Kelly
Chapter 5	Charles Kelly
Chapter 6	Peter Tozer
Chapter 7	Ali Darvishi Boloorani, Alijafar Mousivand
Chapter 8	Ana Vukovic
Chapter 9	Enric Terradellas, Slobodan Nickovic, Alexander Baklanov
Chapter 10	Alexander Baklanov, Utchang Kang, Charles Kelly, Jochen Luther
Chapter 11	Pierpaolo Mudu, Sophie Gumy, Aurelio Tobías, Francesco Forastiere, Michal Krzyzanowski, Massimo Stafoggia, Xavier Querol
Chapter 12	Utchang Kang, Gemma Shepherd
Chapter 13	Charles Kelly

Graphic designer: Strategic Agenda
Photo editor: Corrina Voigt
Layout and design: Strategic Agenda

Chapter contributors:

- Alexander Baklanov (WMO), Xiao-Ye Zhang (China Meteorological Administration) and Utchang Kang (UNCCD) contributed in part to Chapter 2.
- Verona Collantes (UN Women), Juan Carlos Villagran de Leon (United Nations Office for Outer Space Affairs/United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UNOOSA/UN-SPIDER)) and Corinna Voigt (UNCCD) contributed in part to Chapter 3.
- Bojan Cvetkovic (Republic Hydrometeorological Service of Serbia) contributed in part to Chapter 8.
- Abdoulaye Harou (WMO), Ata Hussain (WMO), Sang-Sam Lee (Korea Meteorological Administration), Sang Boom Ryoo (Korea Meteorological Administration), Andrea Sealy (Caribbean Institute for Meteorology and Hydrology), Robert Stefanski (WMO), Ernest Werner (State Meteorological Agency of Spain), Chengyi Zhang (China Meteorological Administration) and Xiao-Ye Zhang (China Meteorological Administration) contributed in part to Chapter 9.
- Miriam Andrioli (WMO), Samuel Muchemi (WMO) and Juan Carlos Villagran de Leon (UNOOSA-SPIDER) contributed in part to Chapter 10.
- Stephan Baas (FAO), Sophie Charlotte VonLoeben (FAO) and Feras Ziadat (FAO) contributed in part to Chapter 12.
- Nick Middleton (Oxford University) contributed in part to Chapter 13.

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Foreword

Sand and dust storms (SDS) are notoriously unpredictable and difficult to manage. This Compendium is the first comprehensive publication that draws from the emerging science to offer the latest information and knowledge on good practice, approaches and frameworks for combating SDS. As addressing the risks posed by SDS and their impacts is an urgent issue requiring collective action, a collaborative approach has been taken to developing this Compendium.

SDS are natural phenomena with multiple impacts on both the environment and people. The scale and scope of these impacts vary from the local to the global, rapid to slow onset, tropics to the Arctic and the land to oceans. Although some SDS impacts can be positive, unfortunately many are negative and highly damaging. They include impacts on health, transportation, agriculture, air and water quality, and industrial production and other sectors. Such impacts disrupt daily life in the affected areas, disregarding political or geographic boundaries and affecting men and women, young and old alike.

The use of natural ecosystems by people – for example through agricultural and pastoral practices, water use, soil management, deforestation and urbanization – can make the occurrence and impacts of SDS worse. Climate change directly and indirectly intensifies these risks. Sustainable natural resource management therefore has a role to play in addressing SDS.

Concerns about the impact of SDS are growing and the global community urgently needs to find effective and coordinated solutions. Global efforts under the United Nations are now focused on two approaches. Firstly, on source mitigation through sustainable land and water management, as encouraged by various global policies, including land degradation neutrality under Sustainable Development Goal target 15.3. And secondly, on the mitigation of negative impacts through preparedness and resilience measures, such as early warning systems, response plans and prepared individuals.

This Compendium adds value to these initiatives by answering two critical questions: what can be done to manage SDS and how?

For example, large-scale SDS emissions are best managed – indeed may possibly only be reduced – at source, where risk reduction is a primary goal. This Compendium presents essential options for mitigating risk and impact, including the management of anthropogenic sources, and its information and guidance is based on disaster risk-reduction principles.

All stakeholders will find relevant and straightforward information that will help them boost their actions as they learn more about SDS in this accessible and adaptable Compendium. It is a powerful tool for those who are looking to make practical and meaningful change.

Ibrahim Thiaw
Executive Secretary, UNCCD

Key messages

SDS challenges

Sand and dust storms (SDS) are given many local names: examples include the sirocco, haboob, yellow dust, white storms, or the harmattan. They are a regionally common and seasonal natural phenomenon exacerbated by poor land and water management, droughts, and climate change. The combination of strong winds and airborne mineral dust particles can have significant impacts on human health and societies. Fluctuations in intensity, magnitude, or duration can make SDS unpredictable and dangerous.

In some regions, SDS have increased dramatically in frequency in recent years. Human-induced climate change, desertification, land degradation, and drought are all thought to play a role. While SDS can fertilize both land and marine ecosystems, they also present a range of hazards to human health, livelihoods, and the environment. Impacts are observed in both source regions, and distant areas affected directly and indirectly by surface dust deposits. The hazards associated with SDS present a formidable challenge to achieving sustainable development.

SDS events do not usually result in extensive or catastrophic damage. However, the accumulation of impacts can be significant. In source areas, they damage crops, kill livestock, and strip topsoil. In depositional areas atmospheric dust, especially in combination with local industrial pollution, can cause or worsen human health problems such as respiratory diseases. Communications, power generation, transport, and supply chains can also be disrupted by low visibility and dust-induced mechanical failures.

SDS are not new phenomena – some regions of the world have long been exposed to SDS hazards. SDS events typically originate in low-latitude drylands and subhumid areas where vegetation cover is sparse or absent. They can also occur in other environments, including agricultural and high-latitude areas in humid regions, when specific wind and atmospheric conditions coincide.

SDS events can have substantial transboundary impacts, over thousands of kilometres. Unified and coherent global and regional policy responses are needed, especially to address source mitigation, early warning systems, and monitoring.

SDS impacts are multi-faceted, cross-sectoral and transnational, directly affecting 11 of the 17 Sustainable Development Goals – yet global recognition of SDS as a hazard is generally low. The complexity and seasonally cumulative impact of SDS, coupled with limited data, are contributary factors. Insufficient information and assessments hinder effective decision-making and planning to effectively address SDS sources and impacts.

SDS responses

The goal of SDS policy and planning is to reduce societal vulnerability by mitigating the effects of wind erosion. A multi-sectoral process bolstered by information-sharing involves short- and long-term interventions, engages multiple stakeholders, and raises awareness of SDS.

Source and impact mitigation activities are part of a comprehensive approach to manage the risks posed by SDS, from local to regional and global scales. Local communities in source areas are directly affected and will need to take very different actions to those impacted thousands of kilometres away. Engagement and participation of all stakeholders is crucial to effective SDS decision-making and policy, underpinned by up-to-date scientific knowledge.

Source mitigation: Land restoration, using soil and water management practices to protect soils and increase vegetative cover, can significantly reduce the extent and vulnerability of source areas, and reduce the intensity of typical SDS events. Such techniques are also vital for land degradation neutrality and when integrated into sustainable development and land-use priorities, will contribute to food security, poverty alleviation, gender equality and community cohesion as well as SDS mitigation goals.

Early warning and monitoring: Any effective SDS early warning system demands a whole-of-community approach. Building on up-to-date risk knowledge, monitoring, and forecasting, all stakeholders (including at-risk populations) participate to ensure that warnings are provided in a timely and targeted manner, and that sector-appropriate actions are taken to reduce or avoid impacts.

Impact mitigation: Preparedness reduces vulnerability, increases resilience, and enables a timely and effective response to SDS events. It involves individuals, communities and organizations as well as industry and businesses. An effective preparedness strategy includes mitigation measures and protective actions informed by robust science, vulnerability analyses, and risk assessments.

Cooperation, collaboration and coordination: The United Nations Coalition on Combating Sand and Dust Storms was launched in September 2019 and has five working groups: adaptation and mitigation; forecasting and early warning; health and safety; policy and governance; and mediation and regional collaboration. The United Nations Coalition will help leverage a global response to SDS through collaboration and cooperation from local to global levels, making the issue more visible, enhancing knowledge-sharing, and mobilizing resources to upgrade existing efforts.

Death Valley, California, ©Marc Cooper, 2016

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Adriel Kloppenburg – April 15th ©Unsplash, 2015

1. Introduction

Chapter overview

This chapter provides an overview of sand and dust storms (SDS), opening with a review of the challenges faced in understanding and addressing their negative impacts. The role of the United Nations System in addressing SDS is summarized and a review of the UNCCD Policy Advocacy Framework to combat Sand and Dust Storms and its links with the Sustainable Development Goals (SDGs) is provided. The chapter closes with the objectives of the Compendium as well as an overview of the content of each of its chapters.

1.1 The challenge of sand and dust storms

Sand and dust storms (SDS) are natural phenomena that can affect almost all sectors of society. An estimated 2,000 million tons of dust are emitted into the atmosphere annually, of which 75 per cent is deposited on land and 25 per cent on the ocean (Shao et al., 2011). The majority of the sand and dust is emitted due to natural conditions (UNEP, WMO and UNCCD, 2016). For more on the physics and nature of SDS, see **chapter 2**.

As natural phenomena, SDS are a critical part of the global climate and environment, with impacts on local and global weather, nutrient cycles and biomass productivity. SDS affect a range of sectors, including health, transport, education, business and industry, agriculture and farming, and water and sanitation.

While a comprehensive global assessment of the economic impact of SDS is yet to be carried out, the research that is available indicates that significant economic costs can be associated with SDS. For instance, SDS impacts on oil and gas operations were estimated to cost Kuwait US$ 9.36 million in 2018 (Al-Hemoud et al., 2019). Meanwhile, the economic impact of one dust storm on 23 September 2009 affecting Sydney and other parts of eastern Australia was estimated at between US$ 229 and US$ 243 million (Tozer and Leys, 2013).[1] **Chapter 6** discusses in detail how to assess the economic impact of SDS.

SDS impact everyone – men, women, boys and girls – but not all in the same way. These differences stem from the gender-based roles in the productive, economic, family and social spheres that equip women and men with different skill sets, capabilities and vulnerabilities. The gender aspects of SDS are discussed in more detail in the **Special focus section: Gender and disaster risk reduction in chapter 3.**

Similarly, SDS affect individuals with a disability in different ways, with a particular impact on those with compromised health. It is crucial that attempts to reduce the impact of SDS understand these differences and address them in order to ensure a fair and equitable approach. More broadly, the protection of all human rights should be integral to understanding and managing SDS.

There are several challenges when addressing the negative impacts of SDS. First, effectively managing SDS requires the wide range of individual negative SDS impacts on society, including SDS caused by human action, to be addressed to ensure that human development continues. Since addressing a single SDS impact or contributing factor will not reduce the risk posed by SDS, a multi-pronged approach is required.

A second challenge is that SDS impacts are multi-faceted, cross-sectoral and often trans-national. For example, in the agricultural sector, ploughing fields can lead to local SDS which may impact the transport sector by contributing to traffic accidents and fatalities. Dust from the Sahel of West Africa can reach the Caribbean. SDS can damage crops (affecting food security) and increase the cost of air filtration requirements for factories producing electronic components. Global and regional weather conditions and changes can increase, or decrease, the intensity and duration of even local SDS events. Under these conditions, cross-sectoral and trans-national approaches and cooperation between stakeholders, actors and partners outside their individual normal scope of activity are required.

A third challenge lies in the diversity of sectors involved, the scales of intervention required, and the range of stakeholders concerned. This challenge involves assuring that all SDS stakeholders have

1 Australian Dollars converted to USD at 2009 exchange rate.

access to sufficient information to take appropriate action to address SDS impacts.

While considerable information on SDS is available from the chapters of this Compendium and the materials cited in the references, no overall packaging of this information into easily accessible format focused on managing the diverse causes and impacts of SDS has yet been developed.

A fourth challenge is that SDS are not widely recognized as a natural hazard that can lead to disaster-level impacts. In general, SDS rarely result in large-scale physical damage or a high number of immediate fatalities: their impacts are often more hidden, for instance increases in illnesses and deaths from complications related to asthma or cardio-vascular disease. In addition, SDS events, triggered by the ploughing of fields or Haboob passage for instance, can lead to fatalities and damages. However, these events are usually isolated in time (occurring during a specific time of the year) and space (developing from and affecting the same locations when they do occur).

Despite the dramatic effects of SDS – such as sand covering crops – the lack of regular reporting on the full range of SDS impacts and the limited quantification of economic impacts (see **chapter 6**) mean SDS are a low-profile hazard (Middleton et al., 2019), with under-recognized disaster impacts. This low profile has resulted in less attention being paid to reducing SDS impacts on vulnerable individuals, at-risk groups and society in general when compared with other hazards. Considering SDS from a disaster risk management perspective is discussed in more detail in **chapter 3**.

Despite these challenges, SDS management is receiving increasing attention at the national level. Countries, including Canada, China, Iran, the Republic of Korea, United States and others, have implemented SDS management efforts (some for decades), with a significant focus on a natural resource management approach. National, regional and global efforts have been implemented to improve SDS forecasts and warnings, with significant support from the World Meteorological Organization (WMO).

1.2 United Nations System engagement on SDS

In 2007, the fifteenth World Meteorological Congress highlighted the importance of the SDS issue and endorsed the launch of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS, https://public.wmo.int/en/our-mandate/focus-areas/environment/SDS/warnings) to facilitate user access to vital information on SDS. The WMO SDS-WAS is global federation of partners organized around regional nodes that integrate research and user communities (WMO, 2015).

At the global level, the United Nations General Assembly (UNGA) adopted the first resolution on SDS, **Combating sand and dust storms** (A/RES/70/195), in 2015 (United Nations General Assembly, 2015). The resolution recognized that SDS pose a significant challenge to sustainable development and underscored the need to promptly undertake measures to address the impacts and challenges they pose to society.

The UNGA adopted additional SDS-relevant resolutions in 2016, 2017, 2018, 2019 and 2020 (United Nations General Assembly, 2016; United Nations General Assembly, 2017; United Nations General Assembly, 2018; United Nations General Assembly, 2019; United Nations General Assembly, 2020). These resolutions acknowledged the role of the United Nations development system in promoting international cooperation to combat SDS and invited relevant institutions, including the United Nations Environment Programme (UN Environment), WMO and the United Nations Convention to Combat Desertification (UNCCD), to address the SDS problem.

In 2017, the UNCCD 13th session of the Conference of the Parties (COP) adopted its first decision on SDS (Decision 31/COP.13) and invited countries to use the UNCCD **Policy Advocacy Framework to combat Sand and Dust Storms** (UNCCD, 2017. See Box 1) to work on addressing the impact of SDS. The Policy Framework presents principles and sets out measures to minimize the negative impacts of SDS in three key areas:

- monitoring, prediction and early warning
- impact mitigation, vulnerability and resilience, and
- source mitigation

In the same decision, the COP invited United Nations entities to assist affected Parties in developing and implementing SDS policies. Further, it requested that the UNCCD Secretariat collaborate with relevant United Nations entities and specialized organizations to assist Parties with implementing the **Policy Framework** and fostering partnerships to facilitate capacity development to mitigate SDS impacts. This **Sand and Dust Storms Compendium: Information and Guidance on Assessing and Addressing the Risks** is part of efforts by the UNCCD Secretariat, guided by the COP (Decision 25/COP.14), working with other United Nations entities and affected countries, to better understand and address the impacts of SDS.

Tsaiga –July 19th ©Unsplash, 2015

Box 1. The UNCCD Policy Advocacy Framework to combat Sand and Dust Storms, 2017

Goal

The ultimate goal is to reduce societal vulnerability to this recurrent hazard by mitigating the impacts of wind erosion and SDS. Policy advocacy will focus on efforts under three headings:

- post-impact crisis management (emergency response procedures)
- pre-impact governance to strengthen resilience, reduce vulnerability and minimize impacts (mitigation)
- preparedness plans and policies

Objectives

The objectives of the **Policy Framework** are to:

- develop national SDS policy based on the philosophy of risk reduction, including legislative and instrumental arrangements, and risk reduction strategies for resilience and preparedness
- enhance North-South and South-South cooperation on SDS management, warning and source mitigation
- increase availability of, and access to, robust comprehensive SDS early warning systems, risk information/communication and risk assessments
- reduce the number of people affected by SDS
- reduce the economic losses and damage caused by SDS
- strengthen resilience and reduce SDS impacts on basic services, including transport
- reduce erodibility and the extent of anthropogenic SDS source areas in the context of land degradation neutrality
- enhance scientific understanding of SDS, particularly in areas such as impacts and monitoring
- enhance coordination/cooperation among stakeholders in SDS action at the national, regional and global levels for strengthened synergies
- increase financial opportunities for comprehensive SDS early warning and source mitigation

Principles

The **Policy Framework** suggests principles for developing and implementing more proactive SDS policies, in particular resilience building and source mitigation. The SDS policy should:

- Establish a clear set of principles or operating guidelines to govern the management of SDS and its impacts. This policy should aim to reduce risk by developing better awareness and understanding of SDS hazards and the underlying drivers of societal vulnerability, along with developing a greater understanding of how being proactive and adopting a wide range of preparedness measures can increase societal resilience.
- Be consistent and equitable for all regions, population groups (bearing gender in mind), and economic sectors, and be consistent with the SDGs. Similarly, achieving sustainable development as set out in these SDGs can help reduce the occurrence and impact of SDS in affected areas.
- Address dust sources occurring in various environments including drylands, agricultural fields, coastal areas and high latitudes. Further, because of the transboundary nature of many SDS events, national SDS policies should be coordinated in international and regional contexts, as appropriate.

- Be driven by prevention rather than by crisis. Reducing the impacts of SDS requires a policy framework and action on the ground, consistent with the **Sendai Framework for Disaster Risk Reduction 2015–2030.**

Priorities for action

The **Policy Framework** suggests a proactive approach to addressing the negative impact of SDS in each of the three interrelated principal action areas:

1. Monitoring, prediction and early warning
2. Impact mitigation, vulnerability and resilience, and
3. Source mitigation

Suggested action areas are as follows:

1. Monitoring, prediction, early warning and preparedness
   a. Identify and map populations vulnerable to SDS for early warning, including health advisories.
   b. Implement comprehensive early warning systems at national/regional levels.
2. Impact mitigation, vulnerability and resilience
   a. Identify and scale up best-practice techniques for physical protection of assets, including infrastructure and agriculture, against SDS in affected areas.
   b. Identify and scale up best-practice strategies to minimize negative impacts of SDS on key sectors and population groups, including women.
   c. Establish and implement coordinated emergency response measures and strategies across sectors based on systematic impact/vulnerability mapping/assessment.
3. Source mitigation
   a. Identify and monitor SDS source areas.
   b. Identify and scale up best-practice techniques for source mitigation.
   c. Highlight synergies among the **Rio Conventions** and related mechanisms and initiatives for SDS source-area mitigation strategies.
   d. Integrate SDS source-area mitigation practices into national efforts towards achieving SDG target 15.3 on "land degradation neutrality" (LDN). SDS source mitigation could be linked to LDN target-setting and included as a voluntary sub-target in source countries.
4. Cross-cutting and integrated actions
   a. Identify best-practice policy options and policy failures at the regional, national and subnational levels.
   b. Identify key SDS knowledge gaps for focused research.
   c. Mainstream SDS into disaster risk reduction.
   d. Build institutional capacity for coordinated and harmonized SDS policy development and implementation at the regional, national and subnational levels.
   e. Explore innovative financing opportunities and other resources needed for SDS actions.
   f. Establish a coordination mechanism and partnership of relevant United Nations organizations for the consolidation of global policy around SDS in order to strengthen synergies and cooperation at the global level.
   g. Establish an international platform for the dissemination of critical data and the exchange of experiences.
   h. Strengthen regional and subregional cooperation.

The links between SDS management and SDGs are summarized in **Figure 1**. These efforts need to ensure that the links between SDS and dependent ecological system continue so that harm to society from disrupting these systems is avoided.

Figure 1. Links between SDS and SDGs

1 NO POVERTY	Reducing air pollution caused by SDS can help families become healthier, save on medical expenses and improve their productivity.
2 ZERO HUNGER	SDS can cause crop damage, negatively affecting food quality/quantity and food security. Reducing desertification/land degradation (including soil erosion) in source areas will help enhance agricultural productivity.
3 GOOD HEALTH AND WELL-BEING	Air pollution caused by SDS poses a serious threat to human health. Many studies link dust exposure with increases in mortality and hospital admissions due to respiratory and cardiovascular diseases.
6 CLEAN WATER AND SANITATION	Dust deposition can compromise water quality because desert dust is frequently contaminated with micro-organisms, salts and/or anthropogenic pollutants.
11 SUSTAINABLE CITIES AND COMMUNITIES	Mitigating SDS disasters will significantly lower the number of people affected and economic losses caused, contributing to safer, more sustainable and more disaster-resilient human settlements.
13 CLIMATE ACTION	Improving land/water use and management in SDS source areas contributes to creating climate-change-resilient landscapes and communities.
15 LIFE ON LAND	Reducing wind erosion in SDS source areas contributes to land degradation neutrality, thereby enhancing the sustainable use of terrestrial ecosystems.
17 PARTNERSHIPS FOR THE GOALS	SDS activities can be part of efforts to strengthen the means of implementation and revitalize the global partnership for sustainable development.

Source: Adapted from **https://sustainabledevelopment.un.org/?menu=1300**.

1.3 Compendium objective and users

The objective of the **Sand and Dust Storms Compendium: Information and Guidance on Assessing and Addressing the Risks** is to provide guidance, tools and methodological frameworks to aid in the development and implementation of policies and activities to reduce the impact of SDS at the national and regional levels. The Compendium is based on the **Policy Advocacy Framework to combat Sand and Dust Storms** (see **Box 1**) and focuses on its three action areas:

- monitoring, prediction and early warning
- impact mitigation, vulnerability and resilience, and
- source mitigation

The primary users of the **Compendium** are expected to come from two groups:

- officials involved in local and national government, emergency management, health, natural resource management, agriculture, livestock, forestry, meteorology, transport, etc.
- community and civil society stakeholders involved in improving local living conditions, promoting development and addressing the needs of groups that are especially vulnerable to SDS impacts.

The Compendium is expected to increase awareness among decision makers and stakeholders about coordinated policies across sectors in mitigating SDS impacts.

1.4 Content of the Compendium

The Compendium content is divided into 13 chapters:

- **Chapter 1** – "Introduction", providing an overview of SDS and the Compendium.
- **Chapter 2** – "The nature of sand and dust storms", providing an overview of the physical nature of SDS.
- **Chapter 3** – "Sand and dust storms from a disaster management perspective", providing an overview of SDS as a hazard and potential disaster. The chapter reviews how SDS can be managed and mitigated and covers the elements that must be considered in SDS forecasting and warning.
- **Chapter 4** – "Assessing the risks posed by sand and dust storms", discussing the concepts behind assessing the risks posed by SDS hazards and disasters.
- **Chapter 5** – "Sand and dust storms risk assessment framework", building on chapter 3, and providing details of two methods: one based on expert opinion and the other based on using community perceptions of SDS threats and impacts to assess SDS risk.
- **Chapter 6** – "Economic impact assessment framework for sand and dust storms", providing a review the concepts behind calculating the economic cost of events and discussing how this can be applied to assessing SDS economic impact.

- **Chapter 7** – “A geographic information system-based sand and dust storm vulnerability mapping framework”, providing a conceptual review of vulnerability to SDS. The chapter describes the technical steps necessary to assess vulnerability using geographic information system (GIS) software. The process described in chapter 7 provides input on vulnerability, which can be added to the expert assessment process detailed in chapter 5 when sufficient data are available.
- **Chapter 8** – “Sand and dust storm source mapping”, covering how to identify and map SDS.
- **Chapter 9** – “Sand and dust storm forecasting and modelling”, covering efforts at the global to national weather service levels to anticipate the development of SDS and where they will have impacts and examining the use of models in these efforts.
- **Chapter 10** – “Sand and dust storms early warning”, providing an overview of the structure and operation of SDS early warning systems.
- **Chapter 11** – “Sand and dust storms and health: an overview of main findings from the scientific literature”, describing the current state of research into the health impacts of SDS.
- **Chapter 12** – “Sand and dust storms source mitigation”, providing an overview of approaches and methods that can be used to manage SDS sources and impacts.
- **Chapter 13** – “Sand and dust storms impact response and mitigation”, outlining ways to reduce the impact of SDS.

Each chapter is prefaced with a short summary of its content and closes with a conclusion recapping what has been covered and implications for addressing the impacts of SDS.

To facilitate easy use of each chapter, references and chapter-specific annexes are included at the end of each chapter, rather than at the end of the Compendium. This allows each chapter to be used as a stand-alone document in practical application. To ensure that each chapter can be used as a stand-alone document, some repetition between chapters has been necessary.

1.5 References

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2. The nature of sand and dust storms

Chapter overview

This chapter provides basic information on sand and dust storms (SDS) as a natural environmental process. It covers definitions of SDS, their role and interaction within the Earth system, SDS source areas and their trajectory, and SDS mechanisms and processes associated with airborne dust. More detailed information on these topics can be found in the Global Assessment of Sand and Dust Storms (UNEP, WMO and UNCCD, 2016).

2.1 SDS definitions

There are numerous sources of small particulate matter in the atmosphere, including sea salt, volcanic dust, cosmic dust and industrial pollutants, but this document refers to mineral particles that originate from land surfaces. These particles are commonly graded according to their size, consisting of clay-sized (<4 microns), silt-sized (4–62.5 microns) or sand-sized (62.5 microns–2mm) material.

There is no strict distinction in the definitions of sand storms and dust storms, since there is a continuum of particle sizes in any storm. Generally, larger particles tend to return to the land surface soon after being entrained and atmospheric concentrations naturally diminish with distance from source areas as material in suspension is deposited downwind by wet and dry processes. Most of the particles transported more than 100 km from their source are <20 microns in diameter (Gillette, 1979).

Dust storms are formally defined by the World Meteorological Organization (WMO) as the result of surface winds raising large quantities of dust into the air and reducing visibility at eye level (1.8 m) to less than 1,000 m (McTainsh and Pitblado, 1987), although severe events may produce zero visibility. There is no equivalent formal definition of sand storms, but storms dominated by sand tend to have limited areal extent and hence localized impacts, including sand dune encroachment.

Dust storms also have local impacts but their smaller particles can be transported much farther – over thousands of kilometres from source, often across international boundaries – which can bring hazardous dust haze to distant locations. Large-scale dust haze events affect areas measured in tens of thousands and sometimes hundreds of thousands of square kilometres.

The duration of SDS events varies from a few hours to several days. Their intensity is commonly expressed in terms of the surface atmospheric concentration of particles and a distinction is typically made between particles with diameters <10 microns (PM_{10}) and those with diameter <2.5 microns ($PM_{2.5}$). Atmospheric PM_{10} dust concentrations exceed 15,000 µg/m3 in severe events (Leys et al., 2011). Hourly maximum $PM_{2.5}$ concentrations can exceed 1,000 µg/m3 during intense dust storms (Jugder et al., 2011).

In chemical terms, the main component of the particles that make up SDS is silica, typically in the form of quartz (SiO2). Other material commonly found in desert dust includes Al2O3, Fe2O3, CaO, MgO and K2O, as well as organic matter and a range of salts, pathogenic microorganisms – including fungi, bacteria and viruses – and anthropogenic pollutants.

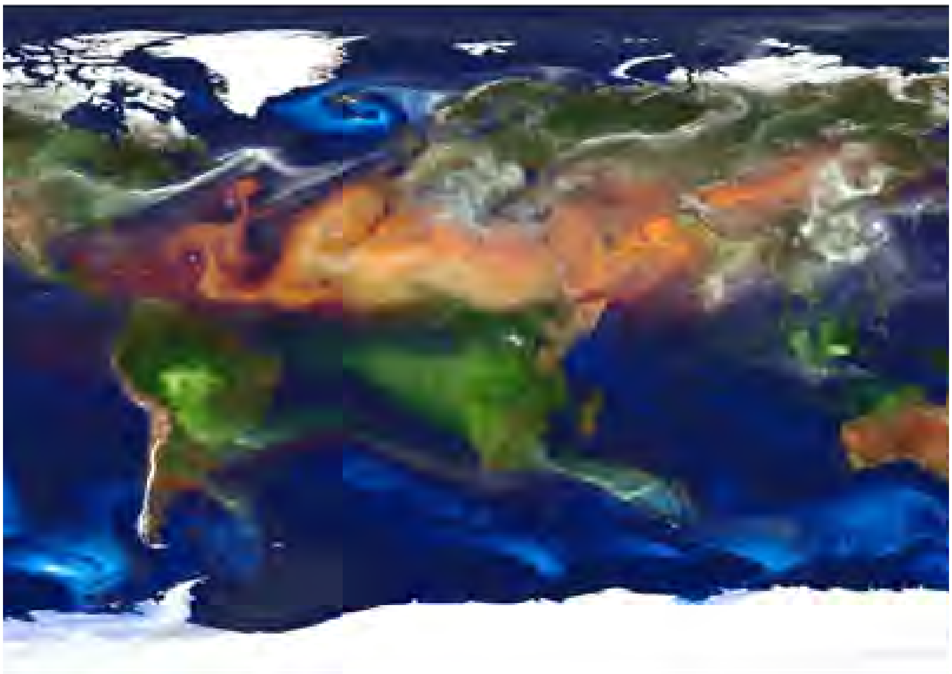
2.2 Atmospheric aerosols

Atmospheric aerosols are liquid or solid particles that originate from both natural and anthropogenic sources and do not distribute homogeneously in the world (see Figure 2). Aerosols classify as primary or secondary. Primary aerosols are directly emitted as particles into the atmosphere under mechanical processes from mainly natural sources such as sea salt from sea spray, mineral dust from dust storms, sulphate from volcanoes, and organic aerosols and black carbon from biomass burning and anthropogenic industrial emissions.

Secondary aerosols form in the atmosphere through gas-to-particle conversion processes from precursor gases (for example H2SO4, NH3, NOx) – which have both natural (for example volcanic eruptions) and anthropogenic origins (for example from fossil fuel combustion) – to particles by nucleation processes, and by condensation and coagulation processes of these particles (Seinfeld and Pandis, 2016). The most abundant secondary aerosols are sulphates, nitrates, ammonium and secondary organic aerosols, which have increased since the last century due to rapid growth in population, urban areas and industrial activities.

Secondary aerosols remain a low contributor to the total atmospheric aerosol mass in comparison with primary aerosols (IPCC, 2013).

Figure 2. Aerosol optical thickness



Note: Aerosol optical thickness of black and organic carbon (green), dust (red-orange), sulphates (white, outside those regions cover by ice as in the Arctic, Antarctic and high-altitude mountain range areas in South America) and sea salt (blue) from a 10 km resolution GEOS-5 Nature-Run using the GOCART model. The screenshot shows the emission and transport of key tropospheric aerosols on 17 August 2006. Source: NASA/GSFC, 2017.

Human exposure to airborne mineral dust may have an adverse effect on human health, causing or aggravating allergies, respiratory diseases and eye infections (Griffin, 2002; Mallone et al., 2011; Tobias et al., 2011). Toxicologists refer to aerosols by their diameter as ultrafine, fine or coarse matter. Coarse particles have an aerodynamic diameter ranging from 2.5 to 10µm (PM_{10} to $PM_{2.5}$), which distinguishes them from the smaller airborne particulate matter referred to as fine ($PM_{2.5}$) and ultrafine particles (PM1).The WHO Air Quality Guidelines (World Health Organization, 2005) provide guidance on thresholds and limits for key air pollutants that pose health risks.

Aerosol impacts also extend to climate, weather, atmospheric chemistry and air quality, but the largest uncertainties concern their radiative impacts (IPCC, 2013). Aerosols alter the atmosphere's radiative balance by scattering and absorbing solar and terrestrial radiation (direct effects) and by changing cloud microphysics and precipitation processes through acting as cloud condensation nuclei/ice nuclei (indirect effects). Research into the impact of aerosols in radiative forcing has grown in recent years because aerosols have been identified as the largest uncertainty among other climate-change causes such as greenhouse gases and changes in pollution.

Soil-derived mineral dust has emerged as one of the most studied aerosols in Earth Sciences. This research reflects the specific and significant impacts of this dust on climate, ecosystems, weather, air quality, human health and socio-economic activities (Knippertz and Stuut, 2014). Soil-derived mineral dust is usually considered natural when wind processes produce it over arid or semi-arid regions characterized by sparse vegetation.

The main large dust source regions correspond with mostly topographically low and natural dried palaeolakes (Ginoux et al., 2001, 2012; Prospero et al., 2002). On the other hand, mineral dust is considered anthropogenic when human activities directly lead to dust emission.

There are large uncertainties regarding the impact of anthropogenic activities on modulating dust emissions:

- directly, for example by altering the properties of land, disturbing soils, desiccating water bodies, removing vegetation, grazing or ploughing, as well as from specific types of land use, for instance, road dust, and
- indirectly, through changes in the hydrological cycle or changes in dust generation due to climate change, including changes in wind and precipitation patterns that favour desertification (IPCC, 2013)

Global annual dust emission from natural and anthropogenic origins are still uncertain. Based on the global models participating in the AEROsol model interCOMparison (AEROCOM) initiative, emission estimates quantified natural dust emissions as varying between 1,000 and 4,000 Tg (IPCC, 2013). Moreover, according to Stanelle et al. (2014), global annual dust emissions have increased from 729 Tg/year in the 1880s to 912 Tg/year in the 2000s. About 56 per cent of this change was attributed to climate change, 40 per cent to anthropogenic land cover changes (for example agricultural expansion), with a 4 per cent natural cycle variability. This division can vary regionally.

Atmospheric mineral dust strongly interacts with the Earth system through direct and indirect impacts (IPCC, 2013). Mineral dust influences the Earth's direct radiative budget by affecting the processes of absorption and scattering at solar and infrared wavelengths. Indirect effects include changes in the number of cloud condensation nuclei and ice nuclei (Atkinson et al., 2013; Nickovic et al., 2016), which in turn affect the optical properties and the lifetime of clouds. Dust particles also have effects on atmospheric chemistry (Krueger et al., 2004).

They can act as a sink for condensable gases and thus facilitate the formation of secondary aerosols, which in turn contribute to PM concentrations.

Dust sedimentation and deposition at the Earth surface causes changes in the biogeochemical processes of terrestrial and marine ecosystems through the delivery of primary nutrients (Jickells et al., 2005). Much of this mineral dust emitted from land surfaces is deposited on the oceans, where it has significant impacts on marine biogeochemistry, marine productivity and deep-sea sedimentation. Dust deposition provides nutrients to ocean surface waters and the seabed, thus boosting primary production, with impacts on the global nitrogen and carbon cycles. In coastal waters in particular, nutrients in desert dust can trigger harmful algal blooms, with knock-on effects on human health and economic activity.

Potential links have also been identified between microorganisms, trace metals and organic contaminants carried in desert dust and some of the complex changes occurring on coral reefs in numerous parts of the world. Elsewhere, it has been demonstrated that the Amazon rainforest is fertilized significantly by Saharan dust (Yu et al., 2015). At the same time, SDS have many negative impacts on the agricultural sector (Stefanski and Sivakumar, 2009).

Regions of the world in the path of dust-laden wind record increased ambient air dust concentrations that are associated with deteriorations in air quality and the strong possibility of negative impacts on human health. Dust events greatly affect the air quality conditions in Asia (for example Wang et al., 2016) and Europe (Pey et al., 2013). Desert dust outbreaks over southern Europe frequently exceed daily and annual safety thresholds of particulate matter set by the European Union directive on ambient air quality and cleaner air (for example Basart et al., 2012; Pey et al., 2013).

As high dust concentrations significantly reduce visibility through increased light extinction, they may affect aircraft operations and ground flights. In addition, dust and sand can damage aircraft engines (Clarkson and Simpson, 2017). Airborne dust is a serious problem for solar energy power plants (Schroedter-Homscheidt et al., 2013). The need for accurate dust observation and prediction products is of importance for plants built in desert areas, for instance in Northern Africa (for example Morocco), West Asia and other arid areas.

2.3 Soil-derived mineral dust in the Earth system

2.3.1. Dust source areas

The world's major dust sources are located in the northern hemisphere across an area called the "dust belt" (i.e. North Africa, the Middle East and East Asia). In the southern hemisphere, with less land mass than the northern hemisphere, dust sources are of smaller spatial extension and are located in Australia, South America and Southern Africa. Significant source areas for SDS are presented in **Figure 3**.

Ginoux et al. (2012) present global-scale high-resolution (0.1°) mapping of sources based on Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue estimates of dust optical depth in conjunction with other data sets, including land use. The analysis ascribes dust sources to natural or anthropogenic (primarily agricultural) origins and calculates their respective contributions to emissions.

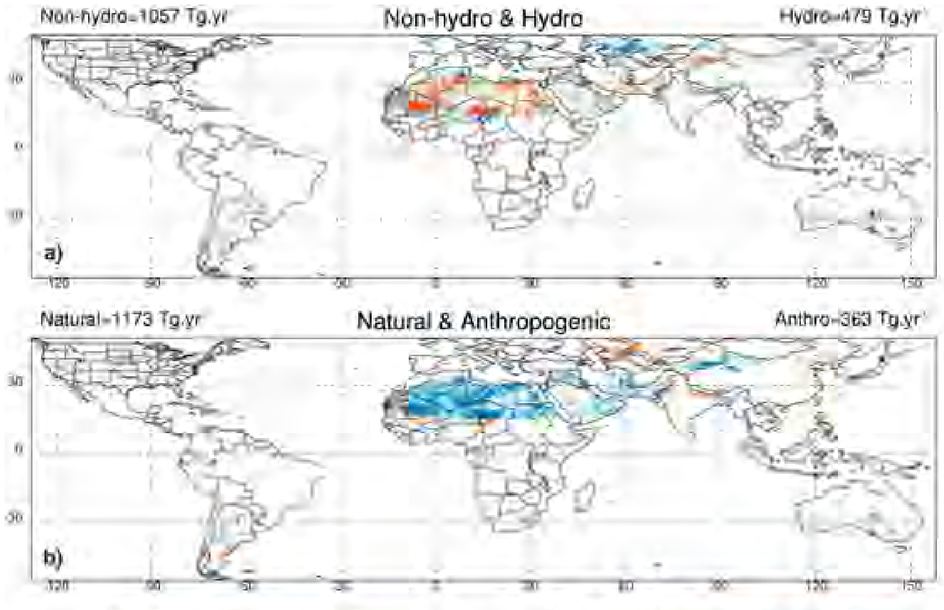


Figure 3. Annual mean dust emission (a) from ephemeral water bodies and (b) from land use

Note: The MODIS Deep Blue emissions are displayed in blue for hydrologic and natural sources and in red for non-hydrologic and anthropogenic sources.
Source: Image extracted from Ginoux et al., 2012, Figure 16.

North Africa is the largest dust source in the world (**Figure 3**). The source zone comprises the Sahara Desert in the north and centre and the semi-arid Sahel in the south. Based on MODIS Deep Blue satellite observations, North Africa accounts for 55 per cent of global dust emissions, of which only 8 per cent are anthropogenic, although it contributes to 20 per cent of global anthropogenic emissions, mostly from the semi-arid Sahel (Ginoux et al., 2012).

In North Africa, emission estimates based on global models widely range from 400 to 2,200 Tg per year (Huneeus et al., 2011). The great uncertainty in dust emission estimates is partly due to the lack of detailed information on dust sources and accounting for small-scale features that could potentially be responsible for a large fraction of global dust emissions (Ginoux et al., 2012; Knippertz and Todd, 2012).

The single largest dust source in the world is located in the Bodélé Depression, north of Lake Chad in North Africa (Ginoux et al., 2001, 2012; Prospero et al., 2002). With the other depressions (such as Aoukar Depression on the Mali-Mauritania border) and the gaps on the downwind side of the Saharan mountains (mainly between 15°N and 20°N latitude), these sources combined can contribute about 85 per cent of all North African dust emissions (Evan et al., 2015).

In **West Asia**, the main dust sources are located in the Arabian Peninsula, such as the Rub' Al Khali desert, one of the largest sand deserts in the world (Ginoux et al., 2012). Other important dust sources are located in Iraq, Pakistan, and parts of Iran and Afghanistan (Goudie and Middleton, 2006; Ginoux et al., 2012; Rezazadeh et al., 2013).

Box 2. Local sources of dust

While the dust belt is the major source of dust circulating globally, local sources of dust can have significant impacts as well.

One typical local source of dust results from ploughing fields, whereby soils can become entrained in winds. While not contributing to the global dust load, these local sources can lead to significant negative impacts, including fatalities (NBC 5, 2017).

Other significant local sources of dust include volcanic ash, for instance in Iceland (Arnalds et al., 2016), and glacial outwash plains (Gisladottir et al., 2005). Identifying SDS sources is also discussed in **chapter 8**.

Emission estimates for West Asia vary from 26 to 526 Tg per year (Huneeus et al., 2011) and seasonal dust activity varies depending on the region. Dust activity peaks in the west of the region during the winter months and shifts to the east from spring to summer when the south-west monsoon is well developed (Prospero et al., 2002).

The most severe dust storms are associated with the summer Shamal (north-westerly winds commonly known as the "wind of 120 days" (Alizadeh-Choobari et al., 2014), which can lift large amounts of dust from their sources and transport them over considerable distances towards the Indian Ocean (Li and Ramanathan, 2002). The Sistan Basin located in eastern Iran and western Afghanistan is the region with the highest number of dust events in West Asia. In the winter, dust storms are mainly caused by the coupling of mid-latitude cold front systems (with winds from the north) and the extent of the southern wind from the Red Sea uplifting dust from many sources at once (Jiang et al., 2009; Kalenderski et al., 2013; Jish Prakash et al., 2015).

A major dust source is located in southern Iraq. The area is situated within Al-Muthanna and Thi-Qar provinces between three major southern Iraqi cities (Al-Nasriya, Al-Diwaniya and Al-Samawa) and within the Mesopotamian Basin and the Samawa and Abu Jir lineaments. The larger zone extends along the Abu Jir fault zone that runs down the western side of the Euphrates River through Karbala, Najaf and west Kuwait. The area contains sand dunes and sand sheets, with an estimated total area of 4,339 km^2 and a perimeter of 895 km. Dust from this source travels through Kuwait, east Saudi Arabia and reaches as far as Qatar (more than 1,200 km away).

Based on visibility measurements, Pakistan is considered a place with a high mean dust concentration (Rezazadeh et al., 2013). Dust storms in Pakistan and north-west India are mainly observed during the pre-monsoon and monsoon seasons from April to September, when dry convection as well as strong downdraft from severe thunderstorms generate dust storms (Hussain et al., 2005; Mir et al., 2006; and Das et al., 2014).

Mesoscale systems, such as sea breezes across the coastal areas (for example the Persian Gulf) and thunderstorms, make an important contribution to dust emissions in West Asia (Miller et al., 2008).

For **Central Asia**, Indoitu et al. (2012) report that the Karakum Desert, northern lowlands of the Caspian Sea and Kyzylkum Desert are major historical SDS sources. In recent decades, desiccated lake beds due to society's overuse of water, such as the Aral Sea in Central Asia (Issanova et al., 2015), have also become significant sources of SDS.

In **East Asia**, the largest natural sources are located in northern China (i.e. Taklamakan Desert, Badain Jaran Desert, Tengger and Ulan Buh Desert, see Figure 4) and Mongolia (i.e. Gobi Desert). Dust storms are more frequent and severe in the spring (Zhang et al., 2003; Ginoux et al., 2012).

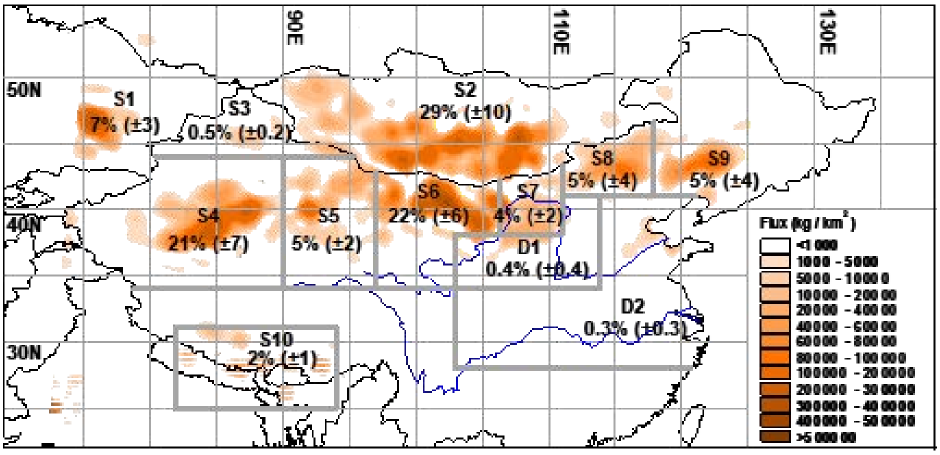


Figure 4. Sources (S1 to S10) and typical depositional areas (D1 and D2) for Asian dust aerosol associated with spring average dust emission flux (kg km^{-2} spring^{-1}) between 1960 and 2002

Source: Zhang et al., 2003.

In **Figure 4**, the percentages with standard deviation in parenthesis denote the average dust emission from each source and depositional areas as a proportion of the total mean emission amount in the last 43 years. The three largest natural sources are located in Mongolia (S2) with Gobi Desert as its main part, northern China high dust region (S6) with Badain Jaran Desert as its main body, and north-western China high dust area (S4) with Taklamakan Desert as its centre. These three main source areas contribute about 70 per cent of total Asian dust emission.

Dust particles are mainly carried eastwards from Central Asia, China and Mongolia to East Asia, Japan and Korea (Zhang et al., 1997; Hong et al., 2010), across the North Pacific Ocean to the western part of North America (Fairlie et al., 2007), and even to the Arctic (Fan, 2013).

About 800 Tg yr–1 of Asian dust emissions are released into the atmosphere annually, about 30 per cent of which is redeposited onto the deserts and 20 per cent of which is transported over regional scales, while the remaining approximately 50 per cent is subject to long-range transport to the Pacific Ocean and beyond (Zhang et al., 1997).

Asian dust appears to be a continuous source that dominates background dust aerosol concentrations on the west coast of the United States of America (Thulasiraman et al., 2002; Fischer et al., 2009). East Asia also contains large anthropogenic dust sources (25 per cent of the total), most of which are found in India and in some regions of China such as the North China Plain (Ginoux et al., 2012; Stanelle et al., 2014).

North American dust activity is concentrated in the south-western United States (Arizona and California) and north-western Mexico. The dust events over this desert area occur most frequently in the spring and rarely during the rest of the year, with the minimum dust activity occurring in winter (Ginoux et al., 2012).

Outside the global dust belt, Australia is the largest dust source in the southern hemisphere (Ginoux et al., 2012). McTainsh and Pitblado (1987) identified the five main high-frequency dust storms regions in Australia: Lake Eyre basin, Central Queensland, the Mallee region, the Nullarbor Plain and the Central Western Australian coast.

Australian dust is transported across the continent along two major routes: east, over the Southern Pacific Ocean and west, over the Indian Ocean (McTainsh, 1989). Ginoux et al. (2012) identified that dust storms mainly occur between September and February in most of the Australian source regions.

Based on Ginoux et al. (2012), **South American** dust sources can be found in: the Atacama Desert (Chile), known as the world's driest region; Patagonia (Argentina); and the Bolivian Altiplano (Bolivia), which contains Salar de Uyuni, the world's largest salt flat. The peak occurrence of dust storms in these regions is between December and February. Large anthropogenic dust sources in the region are predominantly found in Patagonia, where they are associated with livestock grazing (Ginoux et al., 2012).

Southern African dust sources are identified as ephemeral inland lakes, coastal pans and dry river valleys. Southern African dust source locations are mainly found in Namibia (Etosha Basin and Namib coastal sources), Botswana (Makgadikgadi Basin) and South Africa (south-western Kalahari and the Free State).

Dust activity in the region is dominated by the Makgadikgadi and Etosha pans. Low activity is detected throughout the year, but with an increase from the southern hemisphere in summer and autumn (Ginoux et al., 2012; Vickery et al., 2013). Major anthropogenic sources are found north of Cape Town and Bloemhof Dam, from agriculture activities, and in southern Madagascar due to intense deforestation (Ginoux et al., 2012).

2.3.2. Dust cycle and associated meteorological processes

The dust cycle involves several processes such as dust emission, transport and deposition (**Figure 5**), which occur at a wide range of spatial and temporal scales. Based on wind-tunnel experiments (Bagnold, 1941), dust particles are released into the atmosphere through three mechanisms, depending on their size:

- aggregate disintegration for rolling (or creeping) particles larger than 2 mm
- saltation bombardment for particles between 60 μm and 2 mm
- aerodynamic entrainment or suspension of particles finer than 60 μm

Emission processes are also affected by several soil features such as soil moisture, soil texture, surface crust, roughness elements and vegetation (see **Figure 5**).

Once strong winds emit dust particles, fine dust particles are carried by turbulent diffusion and convection to higher tropospheric levels (up to a few kilometres in height) and then large-scale winds can transport them over long distances (Prospero, 1996; Goudie and Middleton, 2006). Dust particles in the atmosphere scatter and absorb solar radiation and, acting as cloud condensation nuclei/ice nuclei, modify clouds and their radiative and precipitation processes (**Figure 5**).

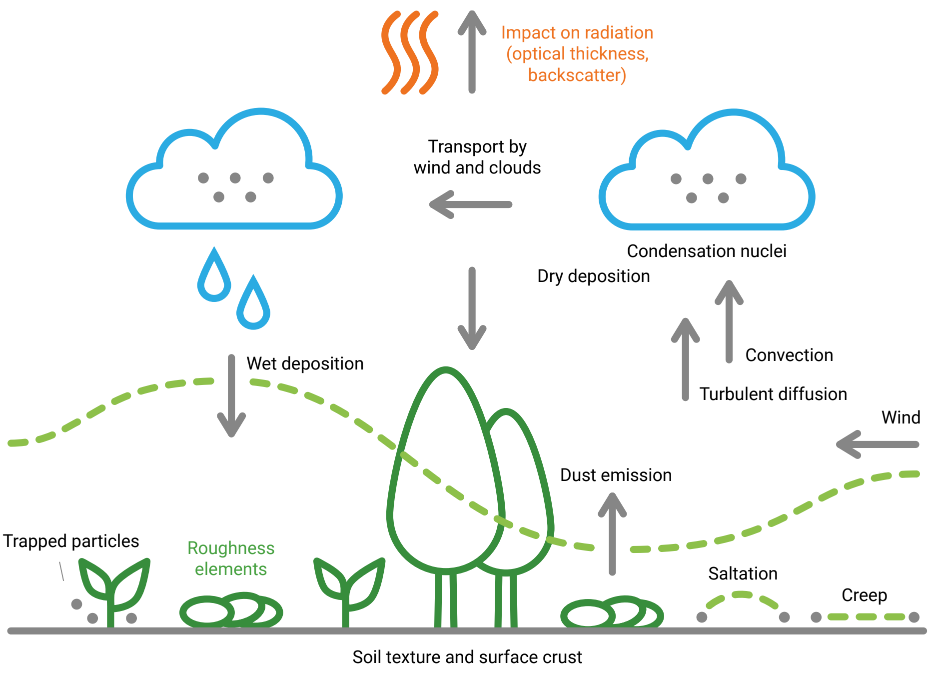


Figure 5. Dust cycle processes, their components, controlling factors and impacts on radiation and clouds

Source: Shao, 2008.

The lifetime of dust particles in the troposphere depends on the particle size. It takes much longer for smaller particles to deposit back on the surface than larger particles. Based on observations, the lifetime of dust particles with a diameter larger than 20 μm is around 12 hours (Ryder et al., 2013). Finer particles can have lifetimes of up to 10 to 15 days, indicating longer transportation distances (Ginoux et al., 2001). These particles are removed from the atmosphere through dry deposition processes, including gravitational settling and turbulent transfer, and wet deposition processes including in- and below-cloud scavenging.

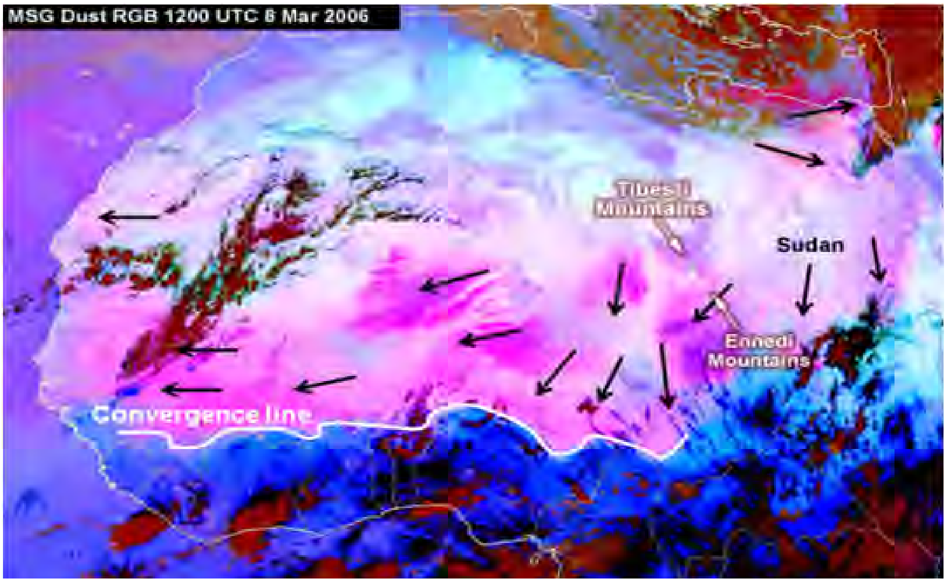
2.3.3. Meteorological mechanisms involved in dust storms

According to WMO, dust storms are generated by strong surface winds that raise a large number of dust particles into the air and reduce visibility to less than 1,000 metres (McTainsh and Pitblado, 1987). There are several meteorological mechanisms, each with its own diurnal and seasonal features, occurring at a wide range of spatiotemporal scales (i.e. synoptic, mesoscale and microscale) that may control strong winds and cause dust storms (Knippertz and Stuut, 2014). These are discussed below.

Large-scale flows mainly associated with monsoon circulations (such as with the Indian and West Africa monsoons, see **Figure 6**), shear-lines (observed both near the ground and in jet streams), and thermal lows over continents (such as the Saharan Heat Low, SHL) affect the emission and transportation of dust by strong large-scale winds over long distances (Knippertz and Todd, 2012). Regions affected by the influence of monsoons are characterized by a reversal of the mean wind direction from summer to winter.

Dust storms caused by large-scale trade winds are typical over the Middle East and North Africa. In North Africa, the large-scale north-easterly trade winds called the Harmattan (see **Figure 6**) are associated with the position of the Intertropical Convergence Zone (ITCZ).

Figure 6. Meteosat Second Generation (MSG) RGB Dust Product for 8 March 2006



Note: The pink regions show dust mobilization caused by large-scale trade winds such as Harmattan (black arrows), which also configurate the Intertropical Convergence Zone (white line).
Source: EUMETSAT, https://www.eumetsat.int/website/home/index.html

During summer in West Asia, these winds blow from the north-west and are called a summer Shamal or the "wind of 120 days", given their persistence from June to September.

Synoptic-scale weather systems (such as cyclones, anticyclones and their cold frontal passage, see **Figure 6**) are the primary control on episodic, large, intense, dust events in many source regions. On the synoptic scale, these are frequently associated with extratropical cyclonic disturbances and particularly the trailing cold fronts with which the latter are associated.

The passage of a cold front that generates dust emission is typically associated with a marked drop in temperature and visibility and increases in wind and pressure (see, for example, Knippertz and Fink, 2006).

The dust frontal zone varies significantly depending on the season and the region as well as the evolution of the cyclone. Pre-frontal dust storms (**Figure 7a**) occur when low-pressure systems move towards a stationary anticyclone or a high topography. Otherwise, post-frontal dust storms (**Figure 7b**) occur when a front passes over the dust source, with the winds generating dust behind it.

Figure 7a

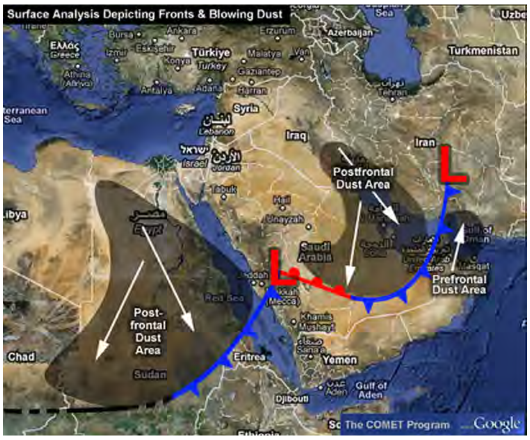


Figure 7b

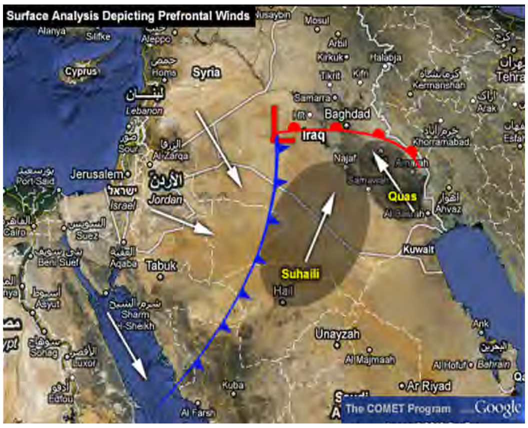


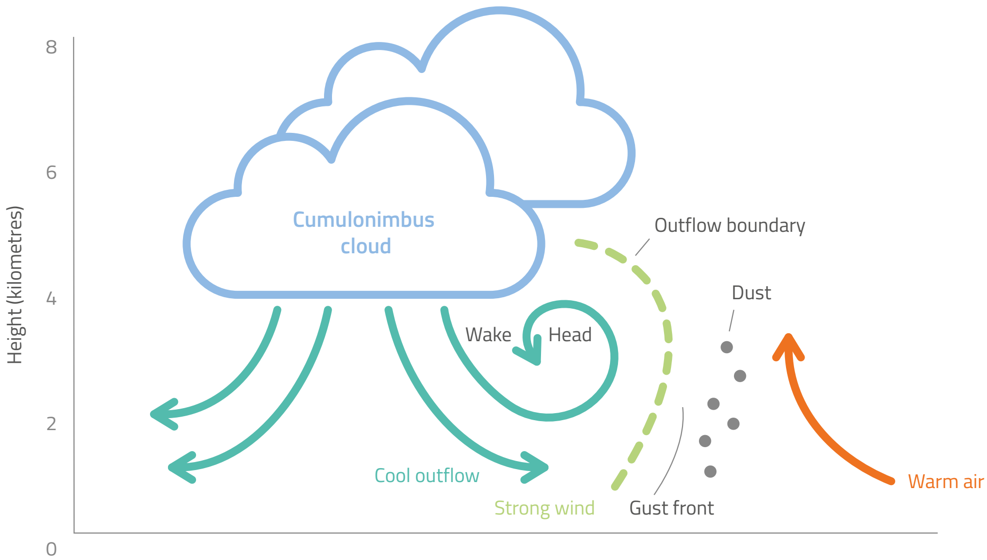
Figure 7a and b. Typical synoptic configurations that can uplift dust over the Middle East

Note: Pre-frontal (**Figure 7a**) and post-frontal (**Figure 7b**) associated sand and dust storms. The Sharqi and Suhaili in yellow in **figure 7a** are winds in the Middle East. Sharqi comes from the south and south-east and Suhaili comes from the south-west, as indicated by the white arrows.
Source: The COMET Program, www.meted.ucar.edu.

Moist convection from cold pool outflows is the main driver of convective mesoscale dust storms, called haboobs. Cold pool outflows are downdrafts caused by the evaporation and cooling of rain from thunderstorms which, near the surface, cause gravity currents where strong winds can uplift dust. Strong winds (the "head" in Figure 8) uplift a large amount of dust and can generate a wall of blowing dust on the leading edge of the haboob where warm air is forced upward by the cold air, forming the "nose" (see **Figure 8**).

Haboobs may reach 1.5 to 4 km in height and span hundreds of kilometres over desert areas. Because of the diurnal cycle of deep moist convection, they tend to occur from late afternoon to night, with a typical lifetime of a few hours (Knippertz and Todd, 2012; Marsham et al., 2013).

Figure 8. Cross section of a haboob

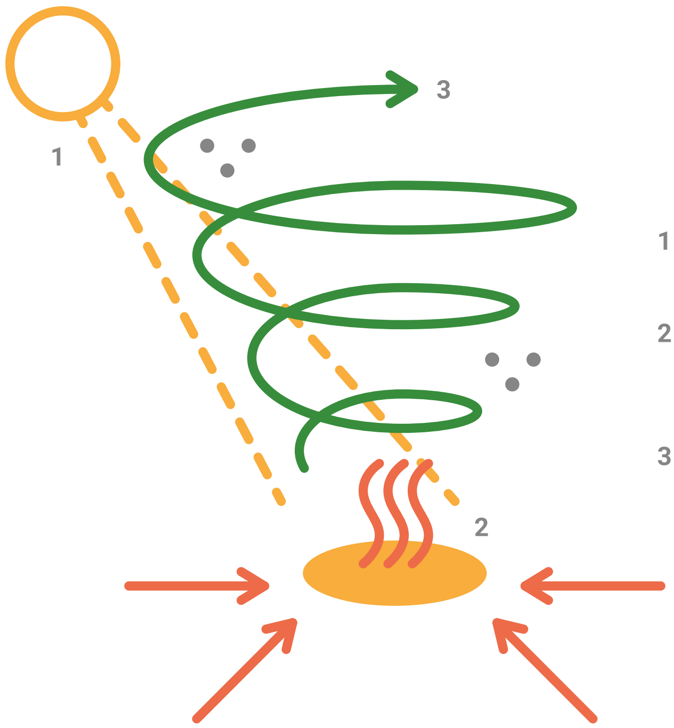


Source: Warner, 2004, Figure 16.10.

Microscale dry convection in the daytime planetary boundary layer (PBL) over deserts can cause dust whirlwinds and dust plumes through turbulent circulation. The most favourable conditions for their formation are clear skies, strong surface heating and weak background winds. Dust whirlwinds have a lifetime from a few minutes to less than an hour and occur at spatial scales from a few to several hundred metres (Knippertz and Todd, 2012).

Figure 9 shows a typical sequence of a dust whirlwind's formation caused by intense surface heating, turbulent winds and microscale dry convection. The Sun heats air nearest the ground. Wind causes the hot air bubble to break through to the stratified layer. Near-surface cyclonic circulation is generated around the low-pressure zone below the newly formed air bubble. Then, in a tetherball effect, the air moves faster as it approaches the centre, then spirals rapidly upward to maintain the dust whirlwind.

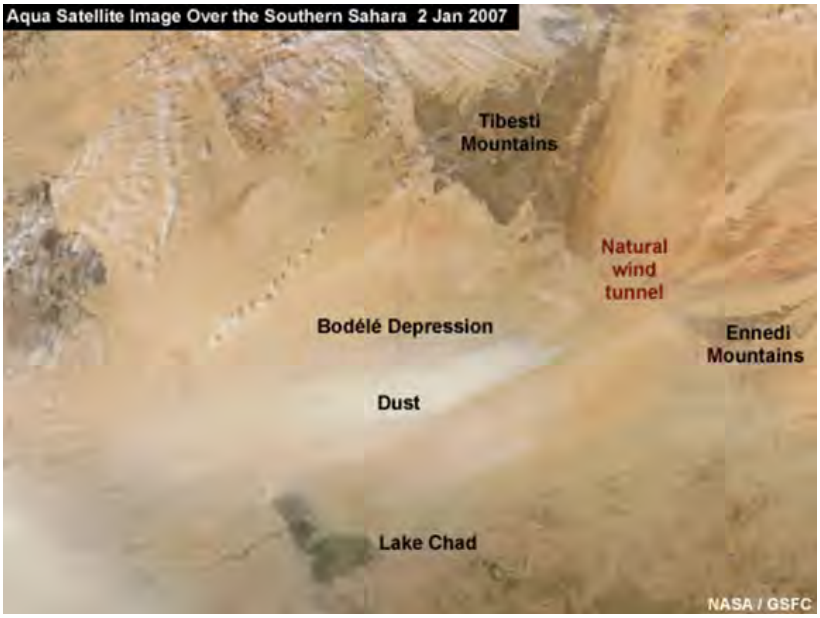
Figure 9. Dust whirlwind formation sequence



1 Sun heats up the ground
2 Warm air rises over the hotspot and pressure lowers
3 Swirling air picks up dust, creating the dust whirlwind

Source: Modified from Ramon Peñas in *The National*, no date.

Figure 10. MODIS true colour composite image for 2 January 2007 depicting a dust storm initiated in the Bodélé Depression, Chad Basin



Source: NASA Earth Observatory, 2007.

Topographic effects can locally affect the meteorology of dust emission and transport processes. This can occur though gaps in mountain ranges channelling wind, as in the Bodélé Depression, the most important dust emission hotspot at the global scale (see **Figure 10**).

Diurnal cycles can also be responsible for dust mobilization. One example is the development and subsequent breakdown of the nocturnal low-level jet (NLLJ). Daytime heating can also set up land–sea or mountain–valley circulations that can be important for the dust emissions in certain regions.

Inversion downburst storms are windstorms that occur on sloping coastal plains with a strong sea breeze. Inversion downburst storms typically lead to a very narrow streamer of dust over the Persian Gulf. As a sea breeze intensifies, convergence along the sea breeze front can generate sufficient lift to break a capping inversion. The resulting instability leads to the downward mixing of cool air aloft, which flows downslope and out over the water. The descending air produces roll vortices and potentially severe local dust storms along the coast. Over time, the inversion is re-established and the event dies out.

2.3.4. Dust seasonality and inter-annual variations

Dust emissions and atmospheric transport from worldwide sources indicate seasonal and spatial variability (Tegen et al., 2002; see **Figure 11**). The data in **Figure 11** are based on Absorbing Aerosol Index (AAI) averages for 1986–1990, organized by season:

- winter (DJF) corresponding to December, January and February
- spring (MAM) corresponding to March, April and May
- summer (JJA) corresponding to June, July, August, and
- autumn (SON) corresponding to September, October and November

The higher (closer to brown) the AAI, the greater the presence of dust particles. The variability is mainly characterized by changes in meteorological conditions in the low troposphere and by global circulation patterns. This includes seasonal displacement of the Intertropical Convergence Zone (ITCZ) (Schepanski et al., 2009) and monsoons (Bou Karam et al., 2008; Cuesta et al., 2010; Vinoj et al., 2014).

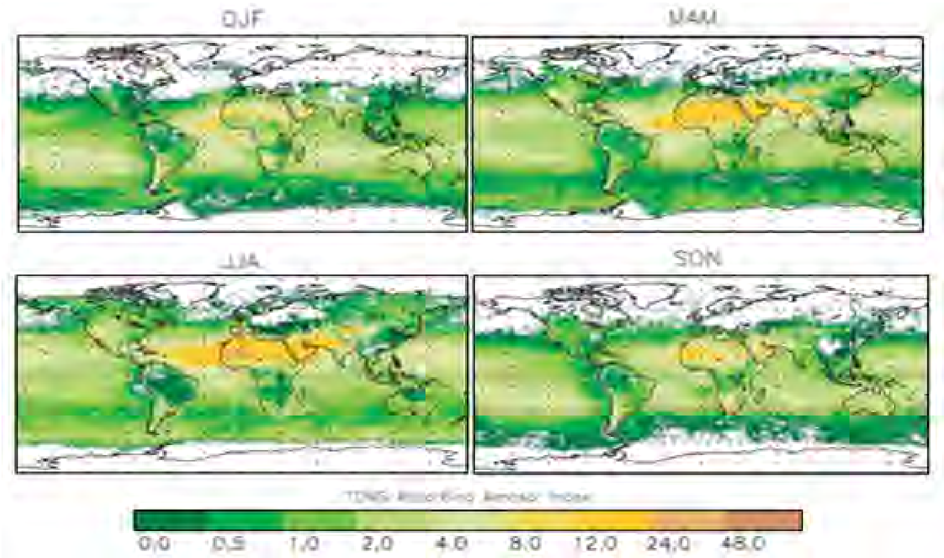


Figure 11. Global seasonal Absorbing Aerosol Index (AAI) based on TOMS satellite imagery

Source: Tegen et al., 2002.

As shown in **Figure 11**, dust activity is associated with a marked seasonality and shifts throughout the year from winter, when it is more pronounced in low latitudes, to summer, when it is observed at higher latitudes (Tegen et al., 2002, 2013; Schepanski et al., 2007). North African[1] dust is mainly transported along three main pathways:

- **Westward** over the North Atlantic Ocean to the Americas (Prospero et al., 2002; Marticorena et al., 2010; Gama et al., 2015). Maximum occurrence is between June and July and minimum from December to February (Prospero, 1996; Basart et al., 2009; Tsamalis et al., 2013).
- **Northward** towards the Mediterranean and Southern Europe. In exceptional outbreaks, dust particles can be transported to Scandinavia and the Baltics (Barkan et al., 2004; Papayannis et al., 2005; Basart et al., 2009; Pey et al., 2013; Gkikas et al., 2016), with a higher occurrence during spring and summer and lower occurrence in winter (Basart et al., 2009; Pey et al., 2013; Gkikas et al., 2016).
- **Eastward** (from East Africa), more frequent in spring and summer towards the Middle East (Goudie and Middleton, 2006; Kalenderski and Stenchikov, 2016), but also possibly as far as the Himalayas (Carrico et al., 2003)

Inter-annual variations in dust patterns also occur. These include differences in African dust transport linked to drought conditions in the Sahel and the North Atlantic Oscillation (NAO) (Prospero and Lamb, 2003; Chiapello et al., 2005), the El Niño–Southern Oscillation (ENSO) in summer (DeFlorio et al., 2016), and surface temperatures over the Sahara (Wang et al., 2015). These inter-annual variabilities and relationships are not yet fully understood but all reveal the connection between dust and climate.

2.4 Conclusions

SDS are atmospheric events involving small particles blown from land surfaces. They occur when strong, turbulent winds blow over dry, unconsolidated, fine-grained surface materials where vegetation cover is sparse or altogether absent. As these conditions are most commonly found in the world's drylands – deserts and semi-deserts – this is where SDS events are most frequent. Sand storms occur within the first few metres above the ground surface, but finer dust particles can be lifted much higher into the atmosphere, where strong winds frequently transport them over great distances. SDS play an integral role in the Earth system, with numerous and wide-ranging impacts including on air chemistry and climate processes, soil characteristics and water quality, nutrient dynamics and biogeochemical cycling in both oceanic and terrestrial environments.

1 The use of "North Africa" and "Northern Africa" refer to the area in Africa north of the Equator and not the area north of the Sahara Desert alone, i.e. the terms encompass parts of what are also called West and East Africa.

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3. Sand and dust storms from a disaster management perspective

Chapter overview

This chapter covers how sand and dust storms (SDS) can be considered a hazard and how hazard and disaster risk management approaches apply to managing their risks and impacts. Also discussed is a unified approach to SDS management and a framework for SDS Risk Management Coordination and Cooperation.

This chapter should be read together with the following chapters:

- 2 – "The nature of sand and dust storms"
- 4 – "Assessing the risks posed by sand and dust storms"
- 6 – "Economic impact assessment framework for sand and dust storms"
- 7 – "A geographic information system-based sand and dust storm vulnerability mapping framework"
- 10 – "Sand and dust storms early warning"
- 12 – "Sand and dust storms source mitigation"
- 13 – "Sand and dust storms impact response and mitigation"

3.1 SDS as a natural hazard

SDS originate from a combination of individual elements, principally wind, sand and dust, but also soil moisture and other factors (see **chapter 2** and **Table 1. Factors associated with sand and dust storms** in **chapter 4**).

As they are triggered by weather conditions, SDS can be classified as a meteorological hazard. However, SDS only occur if specific geophysical and geomorphological conditions are met. This is in contrast with floods, in the sense that enough rain can lead to flooding despite the geology or geomorphology on which the rain falls.

No matter how strong the wind blows, if the geological and geomorphological conditions are not right, an SDS event will not develop. This distinction is not to belabour the uniqueness of SDS compared with other hazards, but rather to stress that assessing and managing the risks from SDS requires attention to be paid to a range of environmental conditions and changes to these conditions over time and space.

Hazards can be classed as rapid/sudden-onset or slow-onset events. SDS are generally linked to negative changes in air quality and land degradation, including soil erosion, and are considered as slow-onset hazards (UNEP, 2012). However, there is a significant question as to whether the rapid-/slow-onset dichotomy is appropriate for SDS. Incremental and cumulative impacts of SDS may be recognized as long-term and slow-onset. Yet, a single severe SDS event can develop in a matter of hours and have significant negative immediate impacts, for instance dust storms leading to large-scale traffic accidents. Understanding slow- and rapid-onset impacts of SDS helps define how and when to reduce these impacts, while paying balanced attention to slow, cumulative and rapid impacts.

The term "sand and dust storms" itself groups different events. Seasonal predominant winds across dry landscapes can lead to high levels of airborne dust and low visibility, as in the Harmattan season in West Africa, with this dust often traveling thousands of kilometres (Middleton, 2017). Haboob, the result of a convective frontal system passing over sand and dust which is entrained by storm winds, can be part of seasonal weather patterns or local changes in weather systems (Roberts and Knippertz, 2012). SDS also develop locally due to wind funnelling through or around mountain ranges for instance, leading to regular afternoons of sand blowing and low visibility that lasts several months. See **chapter 2** for more information on the different types of SDS.

The locations where SDS originate are often characterized as unvegetated or sparsely vegetated dry and subhumid areas. Typical of such areas are the Bodélé Depression in the West African Sahel (Middleton, 2017) and arid areas of Central Asia or Central Australia.

At the same time, SDS can originate from very local conditions. Fields, industrial and mining sites and coastal and urban drylands have all been identified as origins of SDS (Middleton and Kang, 2017). SDS have been reported in Iceland due to high winds blowing across volcanic ash (Dagsson-Waldhauserova et al., 2015) as well as sand and dust created by glacial retreat (Gisladottir et al., 2005). (See **chapters 2** and **8** for more on where SDS can originate.)

The lower limit of wind speed that can initiate an SDS event, in the order of 30 km/hour (NSW Regional Office, 2006), is less than the 62 km/hour or so that it normally takes wind alone to cause damage, based on the Beaufort wind scale (National Oceanographic and Atmospheric Agency, n.d.). Understanding how the right wind speeds and right-sized sand and dust particles come together, often with other factors, to create SDS is an essential step in defining and addressing the impact of this hazard. See chapter 2 for additional details on winds and SDS generation.

No strict distinction exists between sand storms and dust storms. In general, particle sizes in SDS can range from smaller than 60 micrometres (μm) (classified as dust) and from 60 μm to 2,000 μm (classified as sand) (Shao, 2008). The smaller the particle size, the longer the particle is likely to remain in the atmosphere and the further it is likely to travel compared with larger particles.

A single SDS event can be composed of a continuum of mineral particle sizes, although the type of particles at the source area can lead to an SDS event with a specific range of particle sizes. For instance, an SDS event that originates in very fine loess soils will be composed of these particles. Similarly, the particle composition of an SDS event may change as it travels over different types of soils. **Chapter 2** discusses the relation between particle size and entrainment in SDS, while **Figure 5** presents the various aspects that can contribute to a sand or dust storm.

SDS can be triggered by human activity at local to regional scales. The Dust Bowl of the United States is one example of human action that resulted in regional-scale SDS (Egan, 2006). On the local (subnational) scale, ploughing fields in the presence of winds can lead to localized SDS, at times contributing to fatal accidents (Tobar and Wilkinson,1991; Associated Press, 1991).

As a hazard affecting health, the particle size is the main determinant of where dust comes to rest in the respiratory tract once inhaled. A distinction is commonly made between PM_{10} particles, which can penetrate into the lungs, and $PM_{2.5}$ particles which penetrate into deep lung tissue (UNEP, WMO and UNCCD, 2016).

SDS source areas and transport pathways are an important issue given the health implications of the chemical composition of sand or dust, and the potential for contamination through SDS. Atmospheric pollutants can be mixed into SDS that move across heavily industrialized and polluted regions (Chin et al., 2007).

Dust can contain a wide variety of micro-organisms, including fungi, bacteria and viruses, that are capable of causing disease in a range of organisms, including trees, crops, animals and humans (Kellogg and Griffin, 2006). Other potential health-threatening substances that can be found in SDS include heavy metals and pesticide residues (Ataniyazova et al., 2001), polychlorinated biphenyls (Garrison et al., 2006), pollen (Al–Dousari et al., 2016) and arsenic (Soukup et al., 2012).

GLOSSARY OF KEY DISASTER-RELATED TERMS

Disaster: "A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts" (United Nations Office for Disaster Risk Reduction, 2017).

(Disaster) risk: "The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity" (United Nations Office for Disaster Risk Reduction, 2017).

(Disaster) risk assessment: "A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend" (United Nations Office for Disaster Risk Reduction, 2017).

Hazard: an event "…that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (United Nations Office for Disaster Risk Reduction, 2017).

Mitigation: "… lessening or minimizing of the adverse impacts of a hazardous event" (United Nations Office for Disaster Risk Reduction, 2017).

Resilience: The "ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management" (United Nations Office for Disaster Risk Reduction, 2017).

Risk management: The "plans [that] set out the goals and specific objectives for reducing disaster risks together with related actions to accomplish these objectives" (United Nations Office for Disaster Risk Reduction, 2017).

Risk reduction: "… preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development" (United Nations Office for Disaster Risk Reduction, 2017).

Sand and dust storms (SDS): "atmospheric events created when small particles are blown from land surfaces" (Middleton and Kang, 2017). The UNCCD Policy Advocacy Framework to combat Sand and Dust Storms refers to mineral sand (particle size 63 microns to 2mm) and dust (particle size range < 1–63 microns) that originates from land surfaces.

SDS impact mitigation: Reducing the likelihood that sand or dust will have negative impacts at a location on persons, good, services, infrastructure, animals or the environment in general (Middleton and Kang, 2017).

Source mitigation: Reducing the likelihood that sand or dust will be emitted from a location (Middleton and Kang, 2017).

Vulnerability: "The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (United Nations Office for Disaster Risk Reduction, 2017).


Pierpaolo Lanfrancotti, ©Unsplash, January 6th, 2017

Measures to control the generation of SDS from human-caused conditions can be justified as reducing the impact of SDS triggered by human actions. On the other hand, interventions to limit SDS arising from natural (not human-induced) conditions raise questions as to whether these efforts could adversely affect any positive impacts SDS may have on the environment, in some cases at a considerable distance from a source area. Therefore, efforts to control SDS need to assess the risks arising from the events (see **chapter 4** and **5**) and the costs and benefits involved (see **chapter 6**).

Major global trajectory of airborne dust movement and its deposition is documented using GIS techniques and satellite imagery (Ginoux et al., 2012; Shao et al., 2011). Localized and high-resolution point source information on SDS development would help develop appropriate policy measures to reduce impacts. Source mapping is discussed further in **chapter 8**.

SDS can be transboundary hazards affecting source and destination areas separated by long distances. Heavier particles tend to stay in the vicinity of sources (for example sand encroachment and blowing sand). Most dust particles smaller than 20 microns can be transported hundreds of kilometres (Gillette, 1979). Smaller particles can move even further, often thousands of kilometres from the place of origin (Kutuzov et al., 2013; Muhs et al., 2007; Prospero, 1999; McKendry et al., 2011; Grousset et al., 2003; Uno et al., 2009).

The distinction between source and destination is an important aspect of SDS as a hazard as it can dictate the SDS management strategy in affected areas. For example, in source areas, policy priorities are to mitigate the impact of sand or dust being removed by an SDS event, building resilience to these impacts and managing sources, for example by reducing the potential for winds to entrain sand or dust. In destination areas, preparedness and resilience capacity, coupled with early warning, is the key policy component (Middleton and Kang, 2017).

Meteorological and atmospheric dust transport modelling is the key to understanding the relationship between source and impact areas (Benedetti et al., 2014; WMO, 2015). Modelling is discussed further in **chapter 8**.

3.2 Low recognition of the disaster potential of SDS

SDS are not currently well positioned in mainstream natural hazard or disaster research. Middleton et al. (2018) provide a broad overview of SDS as hazards, with some detail on the costs of SDS. The physics (Middleton, 2017; Goudie, 2009) and transport (Middleton, 2017; Baddock et al., 2013) and health (Goudie, 2014) impacts of SDS appear to have been well researched, although there does not seem to be the same level of research coverage for all SDS zones (Pérez and Künzli, 2011).

Much less research appears to have been conducted into economic impacts (Tozer and Leys, 2013; Middleton, 2017; and see **chapter 6**). Social vulnerability to SDS appears to have received little attention, other than in popular literature (Egan, 2006, for instance).

It seems that great attention is paid to SDS in North-East Asia, with the Republic of Korea developing an SDS management plan (UNEP, WMO and UNCCD, 2016). SDS have been the subject of long-term management efforts in the United States of America (Natural Resources Conservation Service, 2017) and Canada (Wang, 2001). At the same time, the disaster risk management priorities of Sahelian countries such as The Gambia, Mali and Niger do not appear to consider SDS as significant, despite Harmattan and haboobs being part of the annual weather cycle of these countries (Gambia, 2017; Niger, Office of the Prime Minister, 2017; Chad, 2017).

The absence of SDS in official statements on hazards facing The Gambia, Niger or Chad contrasts with the research into at least one health impact associated with SDS: the occurrence of meningitis in the Sahel, which suggests a strong link between periods of high atmospheric dust concentrations (and high temperatures) and outbreaks of this disease (Jusot et al., 2017).

Several reasons explain why there is little recognition of SDS. Firstly, SDS usually cause little major structural damage and any immediate physical damage that does occur is relatively minor when compared with other disasters such as earthquakes or floods. Fatalities can be associated with SDS, for instance through traffic accidents caused by haboobs. However, SDS do not usually result in large-scale direct human fatalities or injuries, unlike earthquakes or hurricanes. While SDS do, in fact, contribute to morbidity and mortality, these impacts are often hidden as indirect causes and buried deep in health statistics on respiratory or cardio-vascular diseases, for instance, rather than detailed in dramatic reports of high death tolls directly attributed to a single event.

The economic damage from SDS is often hidden in operating statistics (for example, a greater need to replace air filters during the dust season) or indirect costs of cleaning (see **chapter 6** for more on assessing the economics of SDS.) Other impacts, such as damage to crops or dust and sand covering roads or other infrastructure, are not normally captured in disaster damage reporting.

The EM-DAT[1] ***Annual Disaster Statistical Review 2016: The numbers and trends*** notes that 100 million persons in China were affected by SDS in 2002 but does not report any SDS in 2016 (Guha-Sapir et al., 2017). EM-DAT classes SDS as a meteorological disaster, but the publicly accessible database does not allow the number or impact of SDS as individual events to be identified.[2]
This lack of globally assembled data makes it difficult to provide evidence as to the scale or scope of SDS impacts. National-level data on SDS disaster-related impacts likely varies on a country-to-country basis.

Research into SDS, in terms of either hazards or disasters, is fragmented spatially and topically. Only limited research appears to have been carried out in the Sahel compared with elsewhere, despite it being a major SDS source. Furthermore, less research appears to have been done into the social or economic impacts of SDS than into the physics or health issues associated with these events in some parts of the world.

Reducing the impact of SDS would require the systematic assessment of SDS as a hazard and source of impacts, in order to develop a clearer and evidence-based understanding of these events from local to global scales. Such assessments can provide the knowledge to effectively reduce the negative impacts of SDS on lives and well-being.

1 http://www.emdat.be/.

2 EM-DAT database accessed on 24 November 2017.

SPECIAL FOCUS SECTION: GENDER AND DISASTER RISK REDUCTION

"Women and their participation are critical to effectively managing disaster risk and designing, resourcing and implementing gender-sensitive disaster risk reduction policies, plans and programmes; and adequate capacity-building measures need to be taken to empower women for preparedness as well as to build their capacity to secure alternate means of livelihood in post-disaster situations."

Paragraph 36 (a)(i) Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015a).

International laws and agreements are placing gender equality at the centre of disaster risk reduction (DRR) and resilience-building. At the normative level, the international community has committed to focusing on gender equality and women's rights in DRR.

These commitments are grounded in the **Convention on the Elimination of All Forms of Discrimination against Women** (CEDAW),[3] the **Beijing Declaration and Platform for Action**,[4] resolutions on gender equality and the empowerment of women in natural disasters by the Commission on the Status of Women, and other international agreements.[5] The **Sendai Framework for Disaster Risk Reduction 2015–2030** emphasizes the importance of engaging women in building disaster resilience (United Nations, 2015a).

Despite this focus on gender-responsive disaster risk reduction management, gender perspectives are rarely incorporated into disaster preparedness plans and strategies, vulnerability and risk assessments, and early warning systems (United Nations, 2015b) (see **Figure 12**). Consequently, many institutions and organizations – both national and local – working on disaster risk reduction do not engage women, girls, boys and men equally.

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The result is that:

- the impact of hazards on, and corresponding disaster risks faced by, women and girls are not recognized, and
- the needs and capacities of women and girls are not considered in planning and risk reduction and response activities.

3 The Convention on the Elimination of All Forms of Discrimination against Women (CEDAW), http://www.un.org/womenwatch/daw/cedaw/cedaw.htm.

4 Beijing Declaration and Platform for Action, http://www.un.org/womenwatch/daw/beijing/pdf/BDPfA%20E.pdf.

5 For example: Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters, https://www.unisdr.org/we/inform/publications/1037; Commission on the Status of Women resolution 56/2 and resolution 58/2 on gender equality and the empowerment of women in disasters, http://www.un.org/ga/search/view_doc.asp?symbol=E/2012/27&Lang=E, http://www.un.org/ga/search/view_doc.asp?symbol=E/2014/27&Lang=E

These results perpetuate gendered stereotypes and lead to an increase in women's and girls' vulnerability.

There is good reason to conclude that SDS impact men, women, boys and girls in different ways. Evidence from gender-sensitive disaster research shows that women and men suffer different negative health consequences following extreme events such as floods, windstorms, droughts and heatwaves (Plümper and Neumayer, 2007; IPCC, 2012; Goh, 2013). This effect is strongest in countries where women have very low social, economic and political status.

This highlights the socially constructed and gender-specific vulnerability of women to disasters, which is integral to everyday socioeconomic patterns and leads to relatively higher disaster-related mortality rates in women compared with men (Neumayer and Plümper, 2007).

The gender relations between men and women in disaster risk reduction have everything to do with the roles and responsibilities women and men have at home and in society.

These roles result in different identities, social responsibilities, attitudes and expectations. Such differences are, on the whole, unfavourable to women and lead to gender inequality that cuts across all levels of socioeconomic development, including differences in vulnerabilities to disasters, and different capacities to reduce risk and respond to disasters.

Differences between men and women exist at multiple levels, including:

Roles and responsibilities – Men and women have different roles and responsibilities assigned to them (or expected of them), which can influence their vulnerability to, as well as their capacity to cope with, an SDS event. For example, men are generally expected to secure property and infrastructure, which may lead to them risking their own lives to do this in precarious situations. Women, on the other hand, are expected to prepare the home and attend to children and sick family members.

Access to and management of strategic resources – The ability to access and manage information, training, land, finance, technologies, social networks, support and other strategic resources necessary for well-being and long-term resilience varies between men and women. For example, in some communities, young men may have greater access than women to mobile phones and computers, so they are able to obtain early warning messages or can keep track of an SDS event. Older men and women living on their own may have limited mobility and require the support of others in the community.

People living with disabilities may also require additional time and support to be able to respond to hazards. As women tend to have less access to resources such as cash, housing and vehicles, they have fewer options in responding to disasters.

Participation and decision-making – Men and women may not have the same opportunities when it comes to economic and social participation and political representation. They also have different decision-making powers at the household, community and societal levels. These differences need to be considered to ensure men and women can make choices about their safety, livelihood options and adaptation measures.

However, gender issues are often institutionally marginalized within organizations that do not have enough capacity to advance the issue organization-wide in a multidisciplinary way. Gender issues become perfunctorily treated as "just women's issues", there is a notable absence of male champions, and gender expertise is applied in isolation from processes such as DRR.

Box 3. Women and vulnerability

Women are often presented as a "vulnerable group", with little attention given to the great variety of ways in which they can actively participate in disasters and their role in fostering a culture of resilience. This means that the skills and knowledge that women possess and the powerful role they can play as agents of change within society are often overlooked. In addition, over-generalizations about the vulnerability of women prevent a deep analysis of why some people are more vulnerable than others when disaster strikes.

To be clear, it is not always the case that women are more vulnerable than men to SDS impacts. Some groups of men could also be particularly vulnerable, such as those whose livelihoods depend on agriculture, or who are unemployed, have a disability, are older persons or live alone.

Evidence-based assessment and gender analysis can identify the specific needs of individuals or groups within an affected population. In some circumstances, addressing the specific needs of women and girls may be best performed by taking gender-responsive action because in practice, women and girls may need different treatment to produce equality in outcomes, i.e. to level the playing field so that women can benefit from equal opportunities.

Gender-responsive actions should not stigmatize or isolate the targeted beneficiaries. Rather, they should compensate for the consequences of gender-based inequality such as the long-term deprivation of rights to own property, or of access to financial means, education or health care.

Gender responsive actions should empower women and build their capacities to be equal partners with men in working towards solving problems caused by SDS and helping with reconstruction. Each sector should identify specific actions that could promote gender equality and strengthen women's capacities to enjoy their human rights.

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Cultural practices regarding gender provide some of the most fundamental sources of inequality and exclusion around the world. The underlying roots of gender injustice stem from social and cultural dimensions and manifest themselves through economic and political consequences, among many others.

These long-standing inequalities can be addressed as part of SDS preparedness work. Sound gender analysis from the outset is the key to effective SDS response in the short term and equitable and empowering societal change in the long term.

The needs and interests of women, girls, men and boys vary, as do their resources, capacities and coping strategies in crises. The pre-existing and intersecting inequalities referred to above mean that women and girls are more likely to experience adverse consequences in the event of a sand or dust storm.

In disaster and post-disaster settings, women often find themselves acting as the new head of their households due to separation or loss of male household members. At the same time, they are not always able to access resources and support because there is no assistance for childcare and tasks such as acquiring food or water can be dangerous. As men generally have greater control over income, land and money, their coping mechanisms differ.

Thus, different people within a community may have different vulnerabilities to disasters. It is critical to understand why and how different groups of people may be vulnerable to SDS. Identifying and assessing the determinants of vulnerability will pinpoint where to direct the focus and interventions to reduce vulnerability and increase people's capacity to respond and prepare.

When women and men are included equally in disaster risk reduction, their entire communities benefit. A comprehensive approach to SDS risk management that integrates gender is better equipped to ensure that the particular needs, capacities and priorities of women, girls, men and boys related to pre-existing gender roles and inequalities, along with the specific impacts of the disaster, are recognized and addressed.

Both men and women bring a range of skills and talents to disaster risk reduction. It is vital to identify and leverage all of these available skills to support the long-term resilience of individuals and communities in affected regions.

Mainstreaming gender into SDS risk management can ensure that these efforts equitably benefit women and men while making optimal use of the unique knowledge and skills of both groups. Such equitable engagement is essential to achieving the **Sustainable Development Goals** (SDGs), particularly **SDG 5 – Gender Equality and Women's Empowerment**. Gender equality and women's empowerment are crosscutting issues and prerequisites for achieving many other SDGs, including **SDG 1 – No Poverty, SDG 11 – Sustainable Cities and Communities and SDG 13 – Climate Action**.

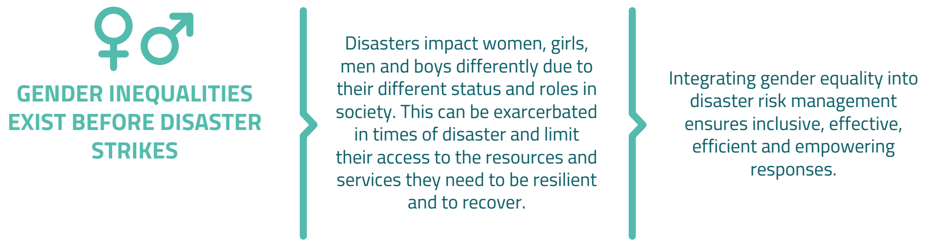

Figure 12. The importance of gender in disaster settings

Source: Adapted from Inter-Agency Standing Committee, 2018.

The following actions, drawn from UNEP (2013), are key to ensuring a gender-responsive approach throughout the integrated SDS risk management planning process:

- Incorporate gender perspectives into SDS risk management efforts at the national, local and community levels, including in policies, strategies, action plans and programmes.
- Increase the participation and representation of women at all levels of the decision-making process.
- Analyse SDS and climate data from a gender perspective and collect sex-disaggregated data.
- Carry out gender analysis as part of the risk profile by documenting the different roles that women and men play in sectors relevant to SDS. For example:
  - How are women and men's livelihoods affected by SDS?
  - How could gender-based differences in decision-making power and ownership of/access to assets lead to different abilities to respond the hazard?
  - What kinds of information do women have and need to better prepare for SDS?
  - What does this imply in terms of differences in vulnerability and coping capacity between women and men?
- Ensure that women are being prominently engaged as agents of change at all levels of SDS preparedness, including early warning systems, education, communication, information, and networking opportunities.
- Consider reallocating resources from the actions planned, in order to achieve gender equality outcomes.
- Take steps to reduce the negative impacts of SDS on women, particularly in relation to their critical roles in rural areas in the provision of water, food and energy by offering support, health services, information and technology.
- Build the capacity of national and local women's groups and provide an adequate platform that presents their needs and views.
- Include gender-specific indicators and data disaggregated by sex and age to monitor and track progress on gender equality targets.

GLOSSARY OF KEY GENDER TERMS

Gender "refers to the social attributes and opportunities associated with being male and female and the relationships between women and men and girls and boys, as well as the relations between women and those between men. These attributes, opportunities and relationships are socially constructed and are learned through socialization processes. They are context/ time-specific and changeable. Gender determines what is expected, allowed and valued in a women or a man in a given context. In most societies there are differences and inequalities between women and men in responsibilities assigned, activities undertaken, access to and control over resources, as well as decision-making opportunities. Gender is part of the broader socio-cultural context. Other important criteria for socio-cultural analysis include class, race, poverty level, ethnic group and age." (UN-Women, OSAGI Gender Mainstreaming - Concepts and definitions)

Gender analysis "is a critical examination of how differences in gender roles, activities, needs, opportunities and rights/entitlements affect men, women, girls and boys in certain situation or contexts. Gender analysis examines the relationships between females and males and their access to and control of resources and the constraints they face relative to each other. A gender analysis should be integrated into all sector assessments or situational analyses to ensure that gender-based injustices and inequalities are not exacerbated by interventions, and that where possible, greater equality and justice in gender relations are promoted." (UN-Women Training Centre, Gender Equality Glossary)

Gender-based evidence (or gender-disaggregated data) "consists of data that: (i) is collected and disaggregated by sex; (ii) reflects gender issues; and (iii) is based on concepts that adequately reflect diversity within subgroups (women and men) and captures all aspects of their lives. This type of data collection takes into account existing stereotypes, and social and cultural factors that cause gender bias." (UNDP/UN-Women (2018), Gender and Disaster Risk Reduction in Europe and Central Asia, Workshop Guide for Facilitators, p. 132)

Gender equality "refers to the equal rights, responsibilities and opportunities of women and men and girls and boys. Equality does not mean that women and men will become the same but that women's and men's rights, responsibilities and opportunities will not depend on whether they are born male or female. Gender equality implies that the interests, needs and priorities of both women and men are taken into consideration, recognizing the diversity of different groups of women and men. Gender equality is not a women's issue but should concern and fully engage men as well as women. Equality between women and men is seen both as a human rights issue and as a precondition for, and indicator of, sustainable people-centered development." (UN-Women Training Centre, Gender Equality Glossary)

Gender issue(s) "refers to any issue or concern shaped by gender-based and/ or sex-based differences between women and men. This may include the status of women and men in society, the way they interact and relate, differences in their access to, and use of, resources, and the impact of interventions and policies on women and men." (UNDP/ UN-Women (2018), Gender and Disaster Risk Reduction in Europe and Central Asia, Workshop Guide for Facilitators, p. 131)

Gender mainstreaming "is the chosen approach of the United Nations system and international community toward realizing progress on women's and girl's rights, as a sub-set of human rights to which the United Nations dedicates itself. It is not a goal or objective on its own. It is a strategy for implementing greater equality for women and girls in relation to men and boys. Mainstreaming a gender perspective is the process of assessing the implications for women and men of any planned action, including legislation, policies or programs, in all areas and at all levels. It is a way to make women's as well as men's concerns and experiences an integral dimension of the design, implementation, monitoring and evaluation of policies and programs in all political, economic and societal spheres so that women and men benefit equally and inequality is not perpetuated. The ultimate goal is to achieve gender equality." (UN-Women Training Centre, Gender Equality Glossary)

Gender perspective "is a way of seeing or analyzing which looks at the impact of gender on people's opportunities, social roles and interactions. This way of seeing is what enables one to carry out gender analysis and subsequently to mainstream a gender perspective into any proposed program, policy or organization" (UN-Women Training Centre: Gender Equality Glossary). "By applying a gender perspective, we can:

- Analyse the causes and consequences of differences between women and men;
- Interpret data according to established sociological (or other) theories about relationships between women and men;
- Formulate inclusive policies and decisions;
- Design interventions that take into account, and address inequalities and differences, between women and men." (UNDP/UN-Women, 2018, Gender and Disaster Risk Reduction in Europe and Central Asia, Workshop Guide for Facilitators, p.30.

Gender-responsive approach "means that the particular needs, priorities, power structures, status and relationships between men and women are recognized and adequately addressed in the design, implementation and evaluation of activities. The approach seeks to ensure that women and men are given equal opportunities to participate in and benefit from an intervention, and promotes targeted measures to address inequalities and promote the empowerment of women." (The GEF, 2017, GEF Policy on Gender Equality)

Gender-sensitive approaches "attempt to redress existing gender inequalities." (UN-INSTRAW [now part of UN-Women], Glossary of Gender-related Terms and Concepts, quoted by Gender Equality Glossary)

Gender stereotypes "Gender stereotypes are simplistic generalizations about the gender attributes, differences and roles of women and men. Stereotypical characteristics about men are that they are competitive, acquisitive, autonomous, independent, confrontational, concerned about private goods. Parallel stereotypes of women hold that they are cooperative, nurturing, caring, connecting, group-oriented, concerned about public goods. Stereotypes are often used to justify gender discrimination more broadly and can be reflected and reinforced by traditional and modern theories, laws and institutional practices. Messages reinforcing gender stereotypes and the idea that women are inferior come in a variety of "packages" – from songs and advertising to traditional proverbs." (UN-Women Training Centre, Gender Equality Glossary)

Sex-disaggregated data "Sex-disaggregated data is data that is cross-classified by sex, presenting information separately for men and women, boys and girls. Sex-disaggregated data reflect roles, real situations, general conditions of women and men, girls and boys in every aspect of society. For instance, the literacy rate, education levels, business ownership, employment, wage differences, dependants, house and land ownership, loans and credit, debts, etc. When data is not disaggregated by sex, it is more difficult to identify real and potential inequalities. Sex-disaggregated data is necessary for effective gender analysis." (UN-Women Training Centre, Gender Equality Glossary)

Women's and girl's empowerment "concerns their gaining power and control over their own lives. It involves awareness-raising, building self-confidence, expansion of choices, increased access to and control over resources and actions to transform the structures and institutions which reinforce and perpetuate gender discrimination and inequality. This implies that to be empowered they must not only have equal capabilities (such as education and health) and equal access to resources and opportunities (such as land and employment), but they must also have the agency to use these rights, capabilities, resources and opportunities to make strategic choices and decisions (such as is provided through leadership opportunities and participation in political institutions)." (UN-Women Training Centre, Gender Equality Glossary)

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3.3 A comprehensive approach to SDS risk management

3.3.1. The disaster risk management overview

Disaster risk management (DRM) is the "application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses" (United Nations Office for Disaster Risk Reduction, n.d.). In practice DRM involves:

- **Preparedness**: the actions taken before a disaster to anticipate the impacts of a possible disaster and measures to reduce these impacts. Preparedness generally covers planning (incorporating results from assessing risks), education, training, stockpiles and ensuring equipment and human capacities are available to respond to a disaster. Educating people identified as "at risk" is a core preparedness task focused on enabling these people to reduce this risk through their own actions.
- **Warning:** the process of providing sufficient information in a timely manner to those at risk and those who provide assistance following a disaster, in order to enable actions to reduce exposure to – or impacts from – the disaster. Developing warning systems is part of preparedness.
- **Response:** the actions immediately after a disaster that save and sustain lives.
- **Recovery:** the set of activities that begin immediately after a disaster and continue through the post-disaster period as people affected by the disaster seek to return to normal life.
- **Risk reduction:**[6] the measures taken before a disaster to reduce risks, either as stand-alone activities or integrated into development efforts.

Disaster risk management is often presented graphically as a cycle, with one component following the other, for example response following warning following preparedness. However, different segments of a society faced with the same hazard may have different levels or depths of engagement with preparedness, warning, response, recovery and risk reduction on account of economic, social and other factors. The level of engagement needs to be considered when defining how each component is achieved and the degree to which one component is strongly or weakly linked to the others, for example warning may be only weakly linked to response for people living in informal settlements.

Chapters 4, 5 and **7** cover risk assessment, the basis for preparedness planning, warning (who should be warned?), response (who will need assistance?) and risk reduction (where is risk reduction needed?). **Chapter 6** provides guidance on how to assess the costs and benefits of risk reduction, **chapter 12** focuses on risk reduction from a source mitigation perspective, while **chapter 13** concentrates on preparedness and response and **chapter 9** covers early warning.

3.3.2. Global approach to SDS risk management

The **Sendai Framework for Disaster Risk Reduction 2015–2030** (United Nations, 2015a) sets out four priorities for action to reduce disaster impact:

1. Understanding disaster risk
2. Strengthening disaster risk governance to manage disaster risk
3. Investing in disaster risk reduction for resilience, and
4. Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.

6 In some cases, efforts to mitigate hazard impacts are intended to reduce risk.

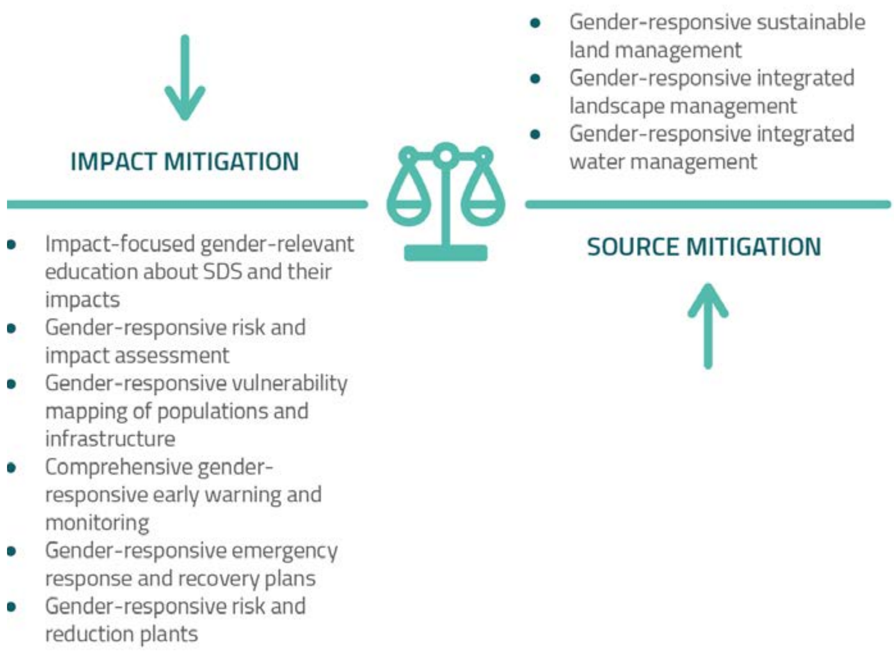
These priority action areas provide a basis for conceptualizing comprehensive SDS risk reduction management.

Drawing on the **UNCCD Policy Advocacy Framework to combat Sand and Dust Storms** (UNCCD, 2017), actions to reduce damage from SDS fall into two areas: impact mitigation and source mitigation. Together, source and impact mitigation activities provide a comprehensive approach to managing the potential disaster risks posed by SDS at local to global scales.
As indicated by **Figure 13**:

- **Impact mitigation** reduces the direct harm from an SDS event through:
  - » impact-focused, gender-relevant education about SDS and their origins and impacts
  - » gender-responsive risk and impact assessment
  - » gender-responsive vulnerability mapping of populations and infrastructure
  - » comprehensive gender-responsive early warning and monitoring
  - » gender-responsive emergency response and recovery plans
  - » gender-responsive risk reduction plans
- **Source mitigation** reduces the potential for harm from an SDS event through:
  - » gender-responsive sustainable land management
  - » gender-responsive integrated landscape management
  - » gender-responsive integrated water management

(See also **chapters 11** and **12** for more information on source and impact mitigation).

Figure 13. A twofold approach to mitigating sand and dust storm hazards for disaster risk reduction



Source: Adapted from Middleton and Kang, 2017.

Equal attention to both impact and source mitigation is required for two reasons. First, the majority of SDS are natural events. One hundred per cent source mitigation is unlikely to be practical and could have other negative impacts. As a result, the potential for harm from SDS cannot be avoided.

Second, SDS can arise from very local or distant sources. For local sources, even short gaps in mitigation can lead to deadly SDS events, as in the case of ploughed fields next to a highway during strong afternoon winds, where an SDS event can be generated in a matter of minutes and last less than an hour.

For distance sources, an SDS event thousands of kilometres from a location can have an impact, for instance on people with breathing problems. Given the uncertainty as to when and where SDS will develop and have impacts, prudence calls for preparedness to mitigate impacts.

For impact mitigation, most of the actions identified can be integrated into common practice approaches. In most cases, it is feasible for existing severe weather warning systems to include SDS.

Measures to reduce impacts can be included in existing school and community disaster awareness education efforts. Health care system standard operating procedures and traffic management protocols can be adjusted to incorporate measures for managing SDS impacts. This said, further work on recovery interventions is likely needed due to the range and diversity of SDS impacts in contrast to flooding, for instance, where considerable infrastructure repair can be required.

Risk reduction in impact areas will generally overlap with source mitigation interventions. This is because:

- some impacted locations may also be sources of SDS particles, and
- sustainable land management-related interventions are often linked to other risk reduction measures for floods and other hazards.

Thus, on the ground, impact mitigation and source mitigation may take place in the same location and be linked to other risk reduction interventions. The advantages of this situation are that:

- at-risk communities can engage in both preparing for and reducing the risk of SDS, and
- single risk reduction measures, such as tree planting or wetlands rehabilitation, may reduce the risk from several hazards at the same time

In terms of SDS source mitigation, it is worth noting that to be effective these activities generally have to take place at scales that are more comparable to river-basin-wide flood management (for example a system of flood management dams and several different types of land-use interventions). These large-scale interventions present specific challenges in terms of funding, engagement of the population in the target area, and the lag time between interventions such as tree planting and dune stabilization and reduction in SDS intensity.

The following sections review in more detail the approaches identified in the **UNCCD Policy Advocacy Framework to combat Sand and Dust Storms** (UNCCD, 2017) to reduce the impact of SDS (see **chapter 1**). These reviews provide an introduction to the more detailed technical materials in the following chapters of the report.

3.3.3. Risk knowledge

A precise understanding of disaster risk is a principal step in the disaster management process and facilitates appropriate decision-making on risk mitigation and adaptation strategies. SDS risk assessment results, based on a systematic and gender-responsive analysis, provide results that are useful throughout the SDS management lifecycle covering prevention and risk reduction, preparation and warning, and response and recovery.

Gender-responsive vulnerability mapping, as part of the risk assessment process, identifies the level of impact by SDS on at-risk populations. These results inform adaptation and mitigation strategies to help protect human health and prevent crop, property and other damage.

Vulnerability maps can be produced using geographic information system (GIS) software which combines satellite-derived Earth observation information with data on social conditions and status, occupations, economic conditions, institutions, health conditions, wealth, culture, and political conditions, disaggregated by age and gender, to provide detailed answers to the following questions:

- Who is vulnerable to SDS, with details related to sex, age and disability?
- What is the degree of vulnerability?
- What are the reasons for this vulnerability?

Vulnerability mapping:

- informs decision makers and policymakers on the severity and extent of the SDS risks, and who is most vulnerable, and
- provides information to local government; emergency, health and social welfare officials; civil society and other stakeholders on where to direct SDS risk management efforts

Risk assessments and vulnerability assessments are discussed further in **chapters 4, 5** and **7**.

3.3.4. SDS source mapping and monitoring

SDS are part of a small group of natural hazards where the origin of the hazard can be far away from the impact area. In some cases, impact areas are located thousands of kilometres away across country borders. Precise and up-to-date information on SDS sources is critical to forecasting and early warning, as well as to targeting where source mitigation will be the most effective.

Global trajectory and deposition of dust plume movements are relatively well documented. Major global dust sources include North Africa and North-East, East, Central, South and West Asia (Shao et al, 2011; Ginoux et al., 2012; Goudie and Middleton, 2006; Prospero et al., 2002). However, more work is needed to identify and map local and point sources with sufficient resolution, accuracy and local data and information to justify source mitigation efforts. The potential contamination of dust with pathogens and pollutants at source and in transportation also make the precise mapping of SDS dust sources and trajectories important in reducing the SDS risk to human health.

GIS software and models can bring together multiple data sets on precipitation, evaporation, drought, soil moisture, temperature, land and soil degradation, vegetation and land use to improve source area monitoring (Gerivani et al., 2011; Kim et al., 2013; Cao et al., 2015; Borelli et al., 2016). To this process can be added data and analysis from vulnerability mapping to provide a clearer picture of who might be more or less vulnerable during specific SDS events associated with specific weather and socioeconomic conditions. Source area and vulnerability mapping results can also be used in identifying which source mitigation measures can be used to reduce vulnerability. (See **chapters 2** and **8** for more information on source mapping.)

3.3.5. SDS forecasting

Combining SDS source mapping and monitoring, the detection of SDS occurrence and monitoring dust plumes movement and near- and long-term forecasting is core to comprehensive SDS management. Dust raising and transport is monitored using a combination of data from satellites, networks of light detection and ranging (LIDAR) and radiometers, air-quality monitoring and weather stations. Ground-based observations from weather stations provide a powerful, lengthy, standardized data set that extends in some parts of the world continuously for more than 50 years. **Chapter 9** discusses in detail the current global SDS monitoring and forecasting system.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The drawbacks of using dust weather data include the relatively sparse distribution of meteorological stations in key source regions, including the Sahara, parts of Arabia, the Gobi and Taklamakan Deserts and central Australia, as well as the low and often variable frequencies of observations.

However, there is the potential for establishing a citizen science approach to SDS monitoring and warning based on the nature of some SDS genesis in low pressure zones, their movement, knowledge about seasonal or diurnal wind conditions that can generate SDS, and access to weather satellite imagery and forecasts. See **chapter 9** for an example of citizen science SDS monitoring from Australia.

Using citizen science to monitor SDS does not displace official monitoring, forecasting and warning systems, but empowers at-risk populations to be more engaged in the management of the risks they face. This citizen science approach reflects the concept that risk management best starts at the individual level, rather than placing a reliance on top-down communication and on official directives before taking action.

3.3.6. Communication and dissemination of early warnings

For SDS early warning systems to have the desired results, early warning information needs to reach women, girls, men and boys. Equally, the effectiveness of modes of communication and information dissemination is critical to ensuring that vulnerable population groups are aware of, and able to prepare for, a hazard. Gender roles, social status, culture and traditions affect the processing and dissemination of information that people receive through community warning systems. Information flows often fail to reach women, especially those living in remote areas (UNISDR, UNDP and IUCN, 2009).

Disseminating warnings and other SDS-related information can use a range of communication channels, including mobile phone text messages, free-to-air and paid broadcast networks, website updates, emails, word-of-mouth, and open-air warning signals where appropriate (Harriman, 2014). However, care is needed to ensure that messages are clear, have practical value and address the social preference for confirming warnings with other information. Education before actual warnings are sent about the content of warning messages and what to do when a message is received is critical to success when actual warnings are issued.

Technologies such as SMS (short messaging service), WhatsApp, Twitter®, Instagram® or other commercial messaging services can be used in warnings. For instance, in South Korea, warnings of dust events are issued by the Korea Meteorological Administration using local media and SMS text alerts for users who register on their air-quality alert website (KMA, 2019).

However, evidently not all messages sent via SMS or similar technologies are received, or read, immediately and the content of these messages can be very limited. Further, these technologies rely on phone or Internet service, which may not be available in all at-risk locations, or may not be operational due to other factors when warnings need to be issued. SDS early warning is discussed in more detail in **chapter 10**.

3.3.7. Preparedness and response

Preparedness for SDS events is based on asking:

- What is the likely type, frequency and timing of an SDS event?
- Who will be affected, considering gender, age and disability?
- Which measures should be implemented before the event (prior to a warning) and regarding warnings to reduce the impact of an SDS event?

This process uses information from the SDS risk and vulnerability assessments, modelling and past disasters to develop scenarios of expected events. Risk assessment and vulnerability data are used to identify the location of at-risk populations, and why specific groups may be more or less vulnerable, for instance due to health, occupation, housing conditions, gender or wealth.

Preparedness plans generally include warning procedures, specific measures to be taken once a warning has been received as well as when the SDS event is taking place, and education and simulation plans. In general, plans are based on integrating government and civil society activities into the response to a potential disaster. For instance, a preparedness plan may identify that a health centre will call on Red Crescent or Red Cross volunteers to provide support when the number of people coming to the clinic for treatment following the SDS exceeds the human resources available to the clinic.

In many cases, a general preparedness plan for a community, region or nation is complimented by sector-specific plans with additional details for the expected user. For instance, a national preparedness plan would detail the sectoral responsibilities of different departments and services in the event of a sand or dust storm, while each of these parties would have more detailed plans based on the delegated responsibilities.

Globally, some level of disaster preparedness plan exists (whether formal or informal) for almost all towns or similar settlements. It is also common for disaster preparedness plans to exist at the regional and national levels. Given the likely existence of a disaster preparedness plan, the initial steps in preparing for SDS response is to integrate risk and vulnerability information into the plan, followed by developing SDS scenarios and identifying response options. The effectiveness of response options can be tested through a scenario-based simulation, with the whole SDS component complemented by a public education plan using schools, community events and other opportunities.

Actual response to SDS can vary considerably depending on the scale and impact of the SDS event, the level of preparedness and the timeliness of warnings and whether they were followed. As with other disasters, response to SDS is an adaptive process. Critical tasks are to:

1. Assess and document the impacts of the SDS.
2. Establish a response coordinating system (defined in advance in the preparedness plan).
3. Focus initial response on those groups that risk and vulnerability assessments have identified as at high risk (for example older persons, very young children, individuals with compromised health) and consider gender roles and vulnerabilities.
4. Allocate resources to those parties involved in the response that face the greatest need.
5. Initiate discussions and planning on recovery, which should be integrated into the initial response as far as possible. (Information for recovery planning should come from the first task of assessing impacts.)

The **Sphere Handbook**, especially page 11, provides further guidance on responding to disasters (Sphere Association, 2018). Preparedness and impact mitigation (response) are discussed further in **chapter 13**.

3.3.8. Risk reduction

Under the **Policy Advocacy Framework** (UNCCD, 2017), risk reduction takes place through source mitigation and impact mitigation (see **Figure 13**). Broadly, risk reduction focuses on two areas:

- Physical measures that can reduce or prevent the impact of an SDS event. These measures are often based on improved land-use planning and land-use management, as discussed further in **chapter 13**, but they can also include improvements to air supplies in buildings or improvements to roads to reduce SDS impacts.
- Socioeconomic measures that:
  - » reduce the level of damage that an SDS event can cause at the individual or household level
  - » improve the ability of at-risk individuals or groups to address the impacts of the SDS event

The socioeconomic measures include a wide range of possible interventions targeted at addressing a specific impact of an SDS event. For instance, less wealthy families can be provided grants or materials to improve windows and doors to reduce dust infiltration. Individuals with respiratory problems can be provided with breathers and appropriate power supplies at no or low cost. Families identified as more at risk can be offered economic opportunities to generate additional income to self-finance measures for reducing SDS impacts. A significant element in defining and choosing appropriate socioeconomic measures is understanding risk and vulnerability, with education about SDS and risk reduction measures important in enabling a specific at-risk individual or group to select the best options for their needs.

3.3.9. Anthropogenic source mitigation

There are numerous technical measures for mitigating SDS at source (see **chapter 12**), including a wide array of techniques that are used for wind erosion control, most of which were developed to protect cultivated fields from soil loss (Skidmore, 1986; Nordstrom and Hotta, 2004).

At any particular location, a range of measures is typically employed. Riksen et al. (2003) distinguish between techniques designed to minimize actual risk (short-term: for example cultivation practices such as minimum tillage) and those that minimize potential risk (long-term: for example planting windbreaks).

Most of the technical measures are usually applied in places where wind erosion is predominantly an anthropogenic land-use issue. The main exceptions are in desert areas where naturally occurring mobile sand dunes and blowing sand present challenges to human activities.

Action taken to mitigate anthropogenic sources of SDS contributes towards the global aspiration to halt and reverse land degradation by 2030 (**Sustainable Development Goal target 15.3** https://sdgs.un.org/goals/goal15) and is in line with the concept of land degradation neutrality (LDN). Sustainable land use management (SLM), in particular, contributes towards resolving issues surrounding the need to achieve social, economic and environmental objectives in areas where productive land uses compete with environmental and biodiversity goals (Sayer et al., 2013).

3.4 Comprehensive approach to SDS risk management

Given the diverse spatial and temporal nature of SDS, impact and source management require a unified, coordinated cross-sectoral approach. As summarized in **Figure 14**, this approach involves three main groups:

1. **The agencies, institutions and authorities responsible for setting SDS risk management policies and implementing plans covering risk reduction, preparedness, warning and response. Key members of this group include:**
   - » **land and water management authorities, including land reclamation authorities**
   - » **agriculture and livestock ministries**
   - » **health authorities**
   - » **finance authorities**
   - » **meteorology and hydrology services**
   - » **disaster management authorities**
   - » **transport authorities**
   - » **public safety authorities**
   - » **gender/women's ministries/committees**

Jared Verdi, ©Unsplash, October 21st, 2017

2. The scientific research and academic communities responsible for:

   - understanding the social and physical nature of SDS, including risk and vulnerability and the physical mechanics behind the origins of and causes of SDS impacts
   - identifying the ways in which source and impact mitigation policy and practice can be effective and
   - monitoring SDS-related policies and practices to assess effectiveness and define improvements to reduce risk

3. The at-risk communities impacted by SDS and who should be directly empowered to reduce SDS risk through:

   - comprehensive risk management plans covering risk reduction, preparedness, warning and response
   - a solid understanding of the origins and impacts of SDS and measures to mitigate SDS
   - involvement in impact-based warning systems that reflect specific threats and in the means to mitigate these threats
   - involvement in land and water use plans and programmes that can reduce the generation of SDS

In general, at-risk communities include the private sector as well as non-governmental organizations (NGOs) that are involved in risk reduction, preparedness and response. NGOs can vary widely in their nature and focus, from women-led mutual credit groups to international organizations involved in the environment and development. Efforts should be made to involve as many NGOs as possible in addressing the impacts of SDS on at-risk populations.

The process, as indicated in **Figure 14**, is iterative, with a constant exchange between the three groups in an attempt to find better policies and activities to reduce SDS impacts.

This process is also gender-responsive, recognizing that women, boys, girls and men are affected differently by SDS and are presented with different ways of reducing SDS impacts based on their social or cultural roles and expectations. Similar attention is given to young children and older persons as well as those individuals with compromised health, all of whom may be impacted more severely by an SDS event than the general population.

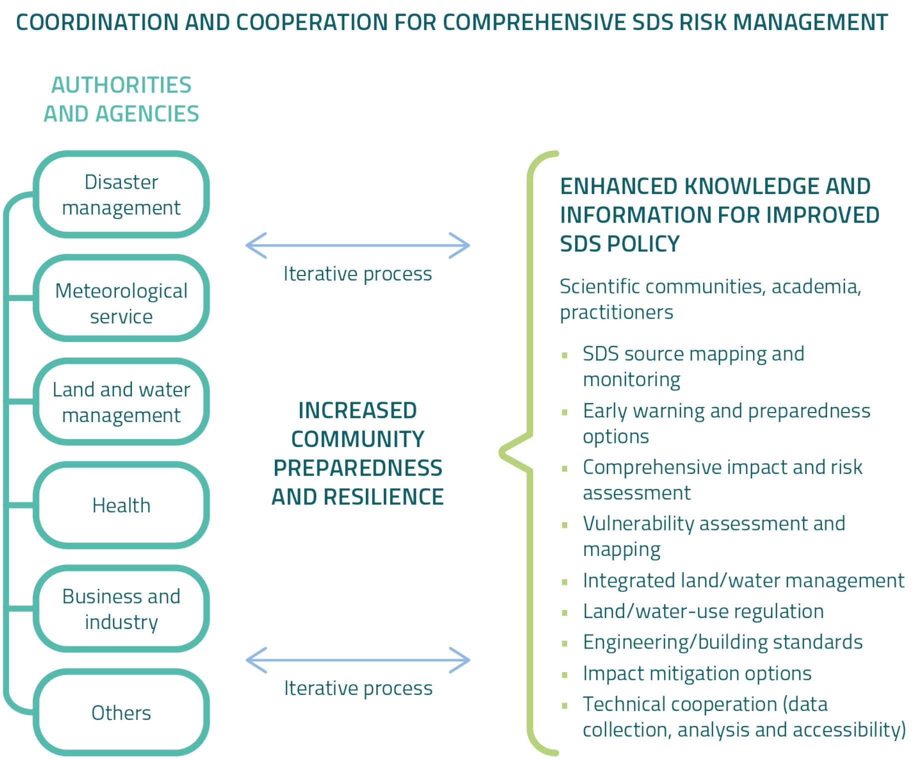

Figure 14. Framework for sand and dust storm risk management coordination and cooperation

Box 4. SDS and a changing climate

SDS are clearly affected by climate conditions, both in terms of climate variability and climate change. **Chapter 3** on climate change and desertification in **Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems** (Mirzabaev et al., in press) reports:

- The loss of vegetation or drying of soil "due to intense land use and/or climate change can be expected to cause an increase in sand and dust storms (high confidence)".
- There is "high confidence that there is a negative relationship between vegetation green-up and the occurrence of dust storms".
- "By decreasing the amount of green cover and hence increasing the occurrence of sand and dust storms, desertification will increase the amount of shortwave cooling associated with the direct effect (high confidence)".
- "There is medium confidence that the semi-direct and indirect effects of this dust would tend to decrease precipitation and hence provide a positive feedback to desertification". However, the "overall combined effect of dust aerosols on desertification remains uncertain".

(All quoted text from p. 268, Mirzabaev et al., in press).

Note that these conclusions relate more directly to desertification than to SDS. Changes to the climate may also affect other factors linked to SDS generation. These include longer periods where seasonal lakes are dry, thus contributing to longer periods of SDS generation, and changes to river flooding duration, where longer low-water periods can provide more source sediment for SDS entrainment.

One of the challenges around understanding the impact of a changing climate on SDS is the lack of extensive weather data collection and observations systems, which limits the understanding of climatic conditions. This same situation also impacts the understanding of SDS, as well as the implementation of warning systems and evaluation of the effectiveness of risk reduction.

Specific approaches to addressing the impact of a changing climate are not included in the Compendium. However, SDS source mitigation approaches incorporating land degradation neutrality, sustainable land management, integrated land management and integrated water use management described in **chapter 12** are all core to addressing the impact of climate on SDS generation and management. Improving the collection and understanding of weather data, at global to local levels, will also contribute to better understanding the links between a changing climate and SDS.

Source: Mirzabaev, A., and others (2019). Desertification. In Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Priyadarshi R. Shukla, Jim Skea, Eduardo Calvo Buendía, Valérie Masson-Delmotte, Hans-Otto Pörtner, Debra C. Roberts, Panmao Zhai, Raphael Slade, Sarah Connors, Renée van Diemen, Marion Ferrat, Eamon Haughey, Sigourney Luz, Suvadip Neogi, Minal Pathak, Jan Petzold, Joana Portugal Pereira, Purvi Vyas, Elizabeth Huntley, Katie Kissick, Malek Belkacemi and Juliette Malley, eds. In press.

3.5 Conclusion

SDS are a significant natural process, but also a natural hazard that is receiving increasing attention. This increased attention is highlighting not only the human, social and economic impact of SDS, but also the ways in which the risks posed by SDS can be addressed.

The efforts to address the impacts of SDS focus on two areas:

- **impact mitigation**, to reduce the direct harm from SDS, and
- **source mitigation**, to reduce the potential for harm from sand and dust

These efforts involve authorities and agencies, scientific research and academic communities and, most importantly, the communities, households and individuals at risk from SDS. The combined effort is iterative and, to be effective and support all those at risk, must consider gender, age and health status.

The following chapters of the Compendium provide more details on how SDS impacts and sources can be managed, how risks and vulnerability can be assessed and how research and data collection can support preparedness, warning and the response to SDS. As indicated by **Figure 14**, this effort is collaborative insofar as it requires the cooperation of many sectors and actors working together in a way that builds on experience and continually improves work to reduce the impact of SDS.

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4. Assessing the risks posed by sand and dust storms

Chapter overview

This chapter discusses the nature of sand and dust storms (SDS) as a hazard and summarizes the differences between risks and impacts. Factors associated with SDS are identified, an SDS typology is proposed and the issue of vulnerability to SDS is explored.

4.1 Assessing SDS disaster risks and impacts

A definition of disaster risk can be found in the **Glossary of key disaster-related terms** (**Chapter 3**). Risk can be understood as the combination of:

- a hazard of a specific magnitude, intensity, spatial extent and frequency (a hazard event)
- exposure of society directly or indirectly to this hazard event
- the level of social and physical vulnerability to this hazard event and
- the capacity to deal with the impact of the specific hazard event

Where there is no exposure to a hazard, there is no risk, and therefore no need for a risk assessment.

Capacity is considered to be the practical opposite of vulnerability. Assessing vulnerability can incorporate any capacity to not experience damage (i.e. reduce vulnerability) from a hazard event. Further background on disaster risk assessment can be found in European Commission (2010) and Schneiderbauer and Herlich (2004).

Box 5 discusses the link between impact and risk assessment. Understanding the potential impact from, or risk posed by, SDS, requires answers to the following three questions:

- What is the physical and spatial nature of the SDS hazard, at different intensities and frequencies?
- How do SDS hazard events (such as Harmattan, haboob and dust storms) affect humans, society and nature, or what is the nature of vulnerability to SDS?
- How can risks from different combinations of SDS intensity and vulnerabilities be compared to identify the optimum points of intervention for reducing these risks?

In general, risk is seen as a negative factor – something that threatens lives and well-being. However, in the case of SDS (as with other hazards), not all of its impacts are negative. For instance, flooding can bring nutrients to flooded fields and SDS can have positive impacts on forestry and the ocean food chain (as cited in Goudie, 2009), or contribute to a dampening effect on hurricane development (University of Wisconsin-Madison, 2008).

At the same time, defining and quantifying trade-offs between positive and negative impacts is complicated; even more so in the case of SDS due to the lack of a full understanding of the links between possible positive impacts and related possible negative impacts. As a result, SDS risk assessment focuses on negative impacts of SDS events, examining how these events interact with human vulnerabilities to cause harm. Once identified, these risks can become the object of efforts to reduce negative impacts on lives and well-being.

Finally, it is critical to understand that risk assessments present a trade-off between accuracy, cost and timely results. Extremely accurate assessments are costly and time-consuming, while rapid inexpensive assessments can deliver contestable or unusable results. The two assessment procedures presented in this chapter can provide usable, and verifiable, results at reasonable costs.

Box 5. Impact and risk

Impact is how an event, real or conjectured, could affect something (for example a river) or someone (for example people living near a river). Post disaster impact assessments document what has happened during and after a disaster. For SDS, such assessments can be used to define future SDS impacts for the same or similar events.

However, information from post disaster impact assessments is not easily used to project the impacts of events that have not yet been experienced, or where there have been significant changes to the environment. Nonetheless, post disaster impact assessments can provide information that is useful in considering the impacts of SDS and they should be conducted whenever possible.

Environmental impact assessments (EIA) take a different approach to assessing impact. An EIA focuses on assessing the impact of a proposed action (for example a road project) and at least one alternative (for example no road) to generate a comparison of impacts and provide input into the best option for achieving a stated goal (such as improving access to a community) (International Association for Impact Assessment and Institute of Environmental Assessment, UK, 1999). The challenge with an EIA-type impact assessment is that its focus on a defined product (such as the construction of a road) and alternatives is difficult to reconcile with understanding the impact of a range of SDS hazard events with varying intensity, duration, recurrence and impacts.

The alternative to the post disaster and the environmental impact assessment approaches is to look at SDS from the perspective of the future risk of impacts on humans, society and the environment in general. These risks, or future impacts, are defined by different combinations of SDS hazard frequency, spatial extent and intensity and the levels of vulnerability of a population threatened by different combinations of these characteristics. This is usually done through disaster risk assessment, where a variety of methods can be used to develop an understanding of SDS impacts under a variety of conditions.

4.2 SDS as hazards

4.2.1. SDS as composite hazards

SDS as a hazard is broadly defined as where blowing sand or dust causes visibility to drop below 1,000 metres (WMO, 2014). The US Air Force recognizes two classes of SDS: one where visibility is between 1,000 and 500 metres and the second where visibility is below 500 metres (Secretary of the Air Force, 2003). These two classes allow for a better differentiation of SDS intensity.

The World Health Organization (WHO) has indicated that, for particulate matter, “no threshold has been identified below which no damage to health is observed” (World Health Organization, 2016). While WHO sets guidelines for small particulate matter, the general finding means that any level of particulate matter found in SDS needs to be considered an active hazard, i.e. a potential source of harm.

To understand what makes an SDS event a hazard, the range of factors that must come together to create it must be defined. The term “sand and dust storms” highlights the composite nature of the hazard, involving sand, dust, storm and a range of other factors.

A single hazard event can be defined by the factors that contribute to (or mitigate against) an SDS event and its spatial coverage (size) or magnitude, intensity, duration and frequency. Also important are the impact and source areas of the event, given how these can affect the other four factors. Nevertheless, even when the factors that normally contribute to an SDS event are present, it is not guaranteed that an SDS event will occur (Middleton, 2017a).

Table 1 sets out the factors that can contribute to, or mitigate against, the development of an SDS event. Each factor is briefly described, together with parameters for measuring it (useful in SDS warning systems) and notes providing additional information on the factor.

The table supports the SDS risk assessment process by identifying what contributes to (and what can reduce) the likelihood of an SDS event. Considering these factors as part of the risk assessment process will improve the accuracy and focus of an assessment.

It should be noted that while SDS events release dust, sand, spores, pollen and other small particulate matter (aerosols) into the atmosphere, not all of these elements in the atmosphere are linked to SDS. A range of aerosols exist in the atmosphere independent of SDS, including particles from fire and other forms of combustion, volcanic ash, pollen and spores (Boucher, 2015). Individually, these atmospheric aerosols can pose significant health and other risks but they are not covered in the assessment apart from their involvement in SDS. (See **chapter 2** for more on what an SDS event comprises.)

Table 1. Factors associated with sand and dust storms

Factor	Description	Parameters	Notes
Wind	Wind speed above a specific level can mobilize sand or dust.	• Speed • Direction • Duration of gusts • Turbulence	Wind speeds needed to create a storm differ under different land-use, land-cover and land-form conditions. Surface level effects, turbulence and fluid dynamics can affect the point or location at which sand or dust become mobile. See Kok et al. (2012) for a detailed discussion of the interactions between wind, sand and dust.
Precipitation (rain and snow)	Rainfall reduces the development of SDS, while periods of reduced precipitation (normal, seasonal or abnormal) can lead to increased likelihood of SDS. Snow-covered land is not expected to be a source of sand or dust, but patchworks of snow-covered and non-covered land may enable SDS generation.	• Cumulative precipitation compared to average • Period of days without precipitation (seasonal precipitation may be average but with extended dry periods) • Snow cover	Humidity levels may be an alternative indicator if high humidity is linked to a lack of SDS. Seasonal snow cover may define seasonality of SDS development. Precipitation can also enhance soil moisture and cohesion (Middleton, 2019).
Drought	The absence of normal levels of rainfall (drought) can lead to dry soils, which are more likely to contribute to SDS. Drought can also cause the reduction or loss of vegetation that provides soil cover or disrupts wind speeds to reduce the generation of SDS.	• Negative change in precipitation compared to short- to long-term averages	Long-term drought can change vegetation and land cover, increasing the likelihood of SDS.
Soil moisture	Soil moisture can affect the looseness of surface soil and its ability to be transported by wind.	• Level of soil moisture	Soil moisture can change with daily heating. Wind can have a drying effect. Soil moisture can be high in the morning following frost or condensed moisture and low in the afternoon/evening due to solar heating and wind.
Ground temperature	Whether the ground is above or below freezing. Freezing temperatures make sand and dust mobilization less likely. High ground temperatures can contribute to convention-related wind speed and dust whirlwinds and can reduce soil moisture and dry the soil.	• Ground temperature	Frozen sand or dust is unlikely to be mobilized by wind. Daily changes from a frozen to unfrozen state may define periods when sand or dust can be mobilized.

Factor	Description	Parameters	Notes
Sand	Sand-sized material can be mobilized by wind of a specific speed under specific ground conditions.	• Presence of sand and in what form: dunes, sheets, alluvial deposits? • Grain size more than 63 microns • Quantity of sand available to be mobilized • Type of land cover • Type of land use	Sand often moves relatively short distances when compared to dust. Wind-blown sand can do damage from pitting as well as filling, covering or piling against infrastructure, or burying vegetation.
Dust	Dust-sized material can be mobilized in an SDS event.	• Grain size less than 63 microns • Quantity of dust to be mobilized • Type of land cover • Type of land use	Dust can usually travel very long distances, particularly if lofted to higher altitudes. Dust clouds are often higher in altitude than blowing sand.
Land cover	Substances and natural and unnatural structures that cover land can protect sand or dust from wind action, either partially or totally.	• Standard land-cover characteristics likely to contribute to sand mobilization should be noted.	Land roughness should be considered as this may disrupt or augment wind movement. Changes in land cover (for instance seasonal ploughing and deterioration in vegetation) can significantly change the potential for sand or dust movement, if only for a short period.
Former or occasional lake beds and other areas usually covered by water[1]	Dry or former lake beds, glacial outwash planes, seasonally dried rivers or flood zones can all become sources of sand or dust when dry.	• Presence of sand or dust in formerly water-covered locations	These source areas can change seasonally or not be active for years, depending on water levels or glacial activity. Some locations can also be relatively inactive when covered by vegetation but activated following ploughing or other human activities.
Land use	How land is being used (impacted by humans)	• Standard land-cover characteristics likely to contribute to sand mobilization should be noted • Soil conservation measures	How land is used (for example ploughing, grazing) can create seasonal or long-term conditions that make sand and dust available for the wind to move. Soil conservation measures (such as no-till ploughing or windbreaks) can affect the availability of sand or dust for movement and wind speeds.

1 Added based on comments by Goudie, 2019.

Factor	Description	Parameters	Notes
Chemicals or minerals	The presence of potentially harmful natural or manufactured chemicals or minerals in source locations	• Antecedent land use • Areas known to contain harmful chemicals or minerals • Chemical analysis of source areas and presence in deposited sand or dust	Research suggests that some minerals and chemicals in sand or dust have positive impacts (Goudie, 2009). Some chemicals present in sand and dust may not be natural but the result of manufactured processes (for example pesticides and residues) or other human-generated processes (for example nuclear explosions).
Pollen and natural organic compounds	Carried by storms in the same way as sand and dust, but with different impacts	• Organic composition of airborne substances	A factor when carried in SDS but not when present due to other weather conditions. These compounds have a variety of impacts through a variety of pathways.
Disease agents	Communicable diseases transmitted together with or on sand or dust	• Presence of disease agents that can be transmitted by wind and sand or dust particles	Whether disease agents can be transported is separate from whether they have an impact.
Other non-pathological organisms	Micro-organisms, including fungi, transported by wind directly or on sand or dust	• Presence of micro-organisms	Organisms may not be pathological but may contribute to or establish a presence in the local ecology.

4.2.2. Spatial coverage, intensity and duration of SDS

The area covered by a specific type of SDS event is important in assessing the overall impact of the event, with intensity and duration also crucial factors. The general assumption is that an SDS event in a larger area will have a greater impact compared with an event of the same intensity and duration covering a smaller area. At the same time, the greater the duration or intensity of an SDS event, the greater the impact it will have when compared with less lengthy or less intense events with the same spatial coverage.

These general assumptions need to be conditioned by possible variations within an SDS event. For instance, wind speed in one part of an SDS event may drop due to local conditions, leading to a reduction in the quantity of dust or sand being moved – or the opposite may occur. Meanwhile, sand or dust size, or the inclusion of chemical contamination or disease agents, in an SDS event may affect the severity of SDS impacts on the environment.

Therefore, within an SDS event, actual intensity and duration need to be assessed at the locations where impact is being assessed. This reflects the weather observation process, whereby observers report on the conditions they observe and not on conditions reported from other sources. While remote sensing may provide improvements in understanding the areal coverage, intensity and duration of SDS, the results would need to be calibrated to the level of individual on-the-ground observers in order to be useful in assessing local impacts.

4.2.3. SDS frequency

Hazard frequency is computed based on the expected return period for an event of a specific intensity and duration at a specific location. It would be useful if return periods were defined on locally based frequency curves, but this may make comparing results across locations difficult if these periods were different.

For the purposes of the assessment, the recommended return periods are 1:1, 1:10, 1:25 and 1:50.[2] As more than one SDS can occur in any one year, and the intensity of SDS conditions can vary within a season, an additional, more frequent, return period can be set at 5:1, or an event once every two months. A risk assessment matrix based on the frequency and intensity of SDS has been suggested and applied to assess SDS events in Kuwait (Al-Hemoud et al., 2019).

Since intensity can vary within an SDS event, and may be less intense at the start and end than during the midpoint, or more intense at the start than the end, the return period should be based on the most intense point of the storm, based on the 1,000 metre visibility threshold. Also note that these return periods are for SDS that can be grouped into specific event typologies (see **Table 2**).

4.2.4. SDS hazard source and impact areas

Global SDS mapping efforts (see UNEP et al., 2016; Huimin et al., 2015) provide a good overview of where SDS originate and where they impact. The global and regional mapping of SDS source and impact areas is important in understanding the global extent of the hazard and how source and impact areas are linked even when a considerable distance apart (for example Sahelian dust in Barbados or Brazil).

However, mapping from a global perspective likely understates the local generation and impact of SDS at the national and subnational scales. This local generation and impact can occur through, for instance, the ploughing of multiple fields over a short period of time during a windy week in the spring, or can arise from winds that move sand on a daily basis but over relatively short distances each day for several months a year, for instance, leading to local sand storms and the movement of dunes across roads or fields, but over a fairly small area.

SDS can actively collect sand and dust during movement, as is the case with SDS associated with convective frontal weather systems (for example a haboob). Observations suggest that this ongoing collection of sand and dust can be a significant contributor to the overall sand and dust load of an SDS event.

Nonetheless, all SDS impacts are local. The assessment of the risks associated with these impacts needs to focus on where the impacts occur. Information on the origin of the sand or dust and factors such as disease or chemical contamination are helpful in understanding impact and risks, and should constitute part of the information collected and reviewed in an assessment, if possible.[3]

It is likely that many SDS source areas are also impact areas. Exceptions, such as Sahelian dust in Barbados, or dust in Korea or Japan, are relatively well documented and can be identified as part of the assessment process. As a result, the SDS assessment process does not need to differentiate between source and impact zones except by noting that both sourcing and impacts are occurring in the same location, if this is the case.

2 While a 1:100 return period is commonly used in risk assessment, it is unclear whether sufficient data are available globally for an assessment at this return period to be possible in most cases.

3 A challenge with assessing chemical or disease components of SDS is that this information often needs to be collected during an SDS event.

The source-impact overlap could pose a challenge in locations where the physical process of sourcing sand or dust leads to significant negative impacts on the environment, for instance erosion damaging vegetation or crop production. Where local source area impacts are considered significant, they can be integrated into the overall SDS risk assessment process by expanding the survey process to consider the impacts of concern (see **chapter 5** on collecting information on SDS impacts).

If specific hazards such as wind erosion or chemical contamination are of significant concern, these hazards should be subject to their own risk assessment. A separate assessment of risks from hazards in a source area can be useful in designing location-specific mitigation measures, for instance to control wind erosion.

4.2.5. SDS hazard typology

A significant range of combinations of winds, sand, dust, land cover and other factors can lead to SDS. The fact that they can move across thousands of kilometres or affect a single small valley adds to the challenge of classifying each SDS event reported.

In reality, SDS risk assessments cannot undertake long-term extensive scientific research to create a detailed classification of SDS events for each location to be assessed. In addition, weather station data, which can be very scarce in a number of the SDS regions, may miss SDS events (for example, a haboob may pass between observations) or a reporting station may be located where localized SDS events occur, such as downwind from a gap in mountains causing localized blowing sand, leading to limited reliability of records of SDS events. (See O'Loingsigh, 2014, for a discussion on using weather station observations to understand SDS events.)

This challenge can be addressed by using a typology of SDS that captures their main characteristics in a uniform and clearly understandable manner. An SDS hazard typology is provided in **Table 2**.

The typology is not intended to present a new scientific definition of SDS, but rather to provide a practical framing of SDS that enables an assessment of relative SDS impacts and risks. Similar typologies are used for earthquakes (Modified Mercalli Intensity Scale, USGS, n.d.) and wind (Beaufort Wind Scale, NOAA, n.d.).

The typology is based on two broad factors:

1. Intensity, defined by the distance of objects visible at eye-level to an observer during an SDS event. This definition of intensity draws on the visibility-less-than-1,000 metres definition (Secretary of the Air Force, 2003), but recognizes the WHO reference to no acceptable minimum level of dust (World Health Organization, 2016). Visibility is used because it is (1) employed as part of the official reporting on weather conditions, (2) easily measured through reference to known objects (for example, is the smoke stack visible?), (3) can easily be included in an assessment questionnaire, and (4) results are relatively less likely to be disputed.

2. Scale, defined by the area covered by an SDS event. Three areal classes are used:

- Small (local) – sand and dust transported over tens of kilometres, generally occurring within part of one country
- Large – sand and dust transported over hundreds of kilometres, generally affecting several countries, or occurring at a regional[4] scale
- Very large – sand and dust transported over thousands of kilometres, generally crossing several countries and often several regions

4 "Region" and "regional" are used here to refer to regions of the globe, not political divisions.

Note that the scale of the event and the scale of the assessment are different. An assessment within a country may consider one or more small-scale events, such as SDS triggered by ploughing, or a very large event, such as dust transported over a great distance, for instance from the Sahel to Brazil. The typology is impact-location-based, in the sense that it is applied where an SDS event is occurring. A small, high-intensity SDS event in one location may be part of a very large, low-intensity SDS event in another location.

Not every SDS event will fit exactly into a grouping in the typology, but any SDS event is expected to fit primarily into one of the six groupings. Outliers can be assigned to groups to which they have the greatest number of common major characteristics.

The typology incorporates:

- the most relevant World Meteorological Organization (WMO) description of SDS characteristics taken from the **Manual on the Observation of Clouds and Other Meteors** (Secretariat, 1975),[5] noted in the table as "WMO" and
- the WMO system for standardized coding of observed weather conditions at the time of observation (see https://www.nodc.noaa.gov/archive/arc0021/0002199/1.1/data/0-data/HTML/WMO-CODE/WMO4677.HTM), noted in the table as "Obs.".

Individual countries also have their own SDS classification systems. For instance, China is reported to use a five-level classification system based on a combination of visibility and wind speed, while the Republic of Korea uses the duration of the presence of sand and dust particle size in the atmosphere (Kang, 2018). These national classification systems can be integrated into the narratives for each type of SDS shown in the table, as part of the background preparation for the assessment procedures detailed in
chapter 5.

It should be kept in mind that the typology is for use among individuals who are not weather experts. The objective is to establish a common understanding of the hazard being assessed by those being interviewed about it.

In the case of the survey-based assessment (**chapter 5.5**), the typology is used to classify perception-based information about SDS affecting those being surveyed. For the expert-based assessment (**chapter 5.6**), the typology aids assessment team members in understanding the hazard being assessed and helps with framing the different types of impacts from different types of events.


Rod Longko ©Unsplash, January 2, 2018

5 The WMO definitions are also available at https://cloudatlas.wmo.int/lithometeors-other-than-clouds.html, with pictures, for reference.

Table 2. Sand and dust storm hazard typology

High intensity, large area (Type One) Frontal generation of dust wall through convection; source and impact areas overlap; can include local movement of sand; high dust density (visibility can drop below tens of metres); hundreds of kilometres long but not very deep; national or subregional; high wind speed (tens of kilometres per hour); often short duration and not persistent; at times with precipitation following; very seasonal (specific months). Example: haboob. WMO: "Dust storm or sandstorm" and Obs.: "Thunderstorm combined with duststorm or sandstorm at the time of observation".	**Low or moderate intensity, large area (Type Two)** Frontal generation of dust; limited source generation in impact area; variable density (visibility rarely down to 1 km, and infrequently lower); hundreds of kilometres long and deep, extending over large areas; long-distance transport possible (thousands of kilometres), national to regional in scale; moderate to no frontal speed, diurnal movement and persistent over days to months; without precipitation; seasonal (range of specific months). Example: Harmattan. WMO: "dust haze" to "dust storm or sandstorm" depending on intensity.
High intensity, small area (Type Three) Windblown sand or dust carried over short distances (tens of kilometres) with prevailing winds (not haboob or Harmattan); source and impact areas can overlap; high speed (tens of kilometres per hour); generally local; often locally significant reduction of visibility; often limited spatial scale but can be frequent and persistent (for example diurnal winds). Example: afternoon sand storms in areas with numerous sand dunes. WMO: "Blowing dust or blowing sand".	**Low to moderate intensity, small area (Type Four)** Windblown sand or dust carried over short distances (tens of kilometres) with prevailing winds (not haboob or Harmattan); source and impact areas can overlap; limited reduction of visibility; limited source or impact areas but can be persistent (for example diurnal winds) over weeks to months; seasonal; without precipitation. Example: blowing dust or sand due to land forms (for example passing between two mountains) that channel and increase wind speed over source areas such as river beds, dryland or dry lake beds. WMO: ""Blowing dust or blowing sand" to "Drifting dust or drifting sand".
High intensity, very small area (Type Five) Windblown sand or dust carried over very short distances (tens of kilometres) due to high speed (tens of kilometres per hour); source and impact areas overlap, very local; often locally significant reduction of visibility; frequent and persistent (for example diurnal winds) or triggered by changes in local conditions. Example: dust from ploughed fields obscuring highways. WMO: "Blowing dust or blowing sand".	**Low intensity, very large area (Type Six)** Regional movement of dust at low density (dust visible but not disruptive to normal activities); source and impact areas different; often at mid-to-high altitude, over large areas; persistent over days or months, but with variable density; seasonal. Example: Dust from the Sahel in Barbados. WMO: "haze" or "dust haze" and Obs.: "Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation".

4.3 Vulnerability to SDS

4.3.1. Defining vulnerability

For this report, vulnerability is understood to be “The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards” (United Nations Office for Disaster Risk Reduction, 2017).

Attention to vulnerability, or the potential impact of SDS, broadly focuses on:

- human health impacts, including illness and fatalities associated with SDS
- economy and industry, including economic and financial impacts and livelihoods
- social impacts, generally related to how SDS affect a person, a family or society, for instance changes in social and gender-based roles as a result of SDS impacts
- political system impacts, including the governance of SDS vulnerabilities and the allocation of power within a society, and
- environmental impacts, including impacts on the ecology and nature resources

Capacity is often used as a counterweight to vulnerabilities, such as in the **Vulnerability and Capacity Assessment** process (International Federation of Red Cross and Red Crescent Societies, 2006). For practical reasons, the focus of assessing vulnerability is on what can be considered “net vulnerability”, that is, taking into account any capacities that may reduce vulnerability.

The concept of resilience is also being increasingly used in association with vulnerability. While the concept has attracted considerable attention, definitions are still in a state of flux, making it hard to apply consistently when assessing vulnerability.[6]

Resilience is considered to be something that occurs after a hazard event has had an impact and has revealed vulnerability. As resilience does not relate directly to the level of impact, but rather the ability to rebound from this impact, it is not incorporated into assessing vulnerability.

This report uses a disaster risk assessment concept for assessing vulnerability to SDS. An alternate approach to defining vulnerability draws on the process of assessing the impact of climate change. In this approach, vulnerability is “… the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change effects” (Parry et al., 2007).

Table 3 provides a more detailed explanation of how the climate change assessment of vulnerability and the disaster risk assessment terminology compare. Per the comparisons in the table, the climate change definition of vulnerability is close to the one used in disaster risk assessment. As a result, the climate change-based assessments of vulnerability (see **chapter 7**) can be integrated into the vulnerability analysis process described in the table.

6 The situation described in Manyena (2006) continues today.

Table 3. Comparison of climate change and disaster risk assessment terminology (Modified from CAMP Alatoo, 2013a)

Term	As applied to climate change assessment	As applied to disaster risk assessment
Exposure	"…background climate conditions against which a system operates, and any changes in those conditions…"	Whether someone or something is in a location that can be affected by a hazard.
Sensitivity	"…the responsiveness of a system to climatic influences, and the degree to which changes in climate might affect it in its current form…"	Incorporated as part of vulnerability.
Potential outcome	Exposure and sensitivity	Incorporated as part of vulnerability.
Adaptive capacity	"Adaptation reflects the ability of a system to change in a way that makes it better equipped to deal with external influences."	Incorporated as part of vulnerability, but only to potential damage and not to risk reduction.
Vulnerability	Exposure, sensitivity, potential outcome and adaptive capacity, as defined in climate change assessment.	The damage that can be done by a hazard event of a specific magnitude, frequency and timing.
Hazard	The change between the current and future climate (e.g. increase in average temperature).	An event that can lead to negative consequences on humans.
Hazard event	Incorporated in Exposure – "…any changes in those conditions".	An occurrence of a hazard of a specific magnitude, timing and frequency.
Frequency	Incorporated in Exposure – "…any changes in those conditions".	How often a hazard of a specific magnitude will occur.
Magnitude	Incorporated in Exposure – "…any changes in those conditions".	The physical scale of a hazard event, measured in a standard metric (e.g. mm of precipitation).
Resilience	Similar to Adaptive capacity but only in relation of a hazard event, not reducing the likelihood of future hazard events.	The means that reduce the initial outcome of a hazard event on six capitals; the means to reduce vulnerability.

The "**As applied to climate change assessment**" column contains quotes from the Australian Greenhouse Office (Allen Consulting Group, 2005). The use of "vulnerability" in climate change assessments is broader than the use of the word in disaster risk assessment. For more on this difference, see Jones et al. (n.d.).

4.3.2. Vulnerability to SDS

Since SDS can vary in size, duration, intensity and so forth, as indicated in **Table 2. Sand and dust storm hazard typology**, assessing vulnerability to SDS must consider the full range of possible impacts (i.e. vulnerabilities) from these events. Middleton and Kang (2017) developed a list of impacts, arranged by sand and dust entrainment, transport and deposition. This list is expanded on below to provide a broad base for considering vulnerabilities as part of the risk assessment process.

Conflict – SDS may take place in ongoing or post-conflict zones. The conflict may induce conditions that increase the likelihood of SDS events (see Tharoor, 2015), or post-conflict recovery may lead to measures to reduce SDS vulnerability, such as re-filling marshes in the Khuzestan Province of south-western Iran.[7]

Economic – These impacts can be associated with disrupted transportation, but also reduced agriculture and animal production (Stefanski and Sivakumar, 2009), and can cause significant loses (as cited in Jugder et al., 2011), as well as contamination of production facilities (for example semiconductor manufacture) and increased operating costs (Kang, 2018). SDS can also cause damage to electrical transmission and communications systems and increase operating costs in the form of higher cleaning and maintenance costs (for example air conditioner filters), and household and business cleaning following the passage of an SDS event (Middleton, 2017b).

SDS events can also affect major national economies, such as the oil and gas operations and oil transport in Kuwait (Al-Hemoud et al., 2019), or flight operations (Al-Hemoud et al., 2017). They can also impact tourism (Tulinius, 2013), with these impacts also shared across transport (for example diverted aircraft) and livelihoods (for example reduced income due to dusty weather reducing tourist excursions).[8] See **chapter 6** for more on the economic impacts of SDS.

Environmental – Apart from location-specific environmental impacts, SDS can also have broad environmental impacts by affecting weather patterns (University of Wisconsin-Madison, 2008), albedo and atmospheric clarity (for example affecting photosynthesis).[9] These impacts are often so broad as to be difficult to assess on an SDS-event-specific basis.

The movement and removal of sand and dust over short or long distances is due to a combination of winds and ground conditions. This movement can reduce soil depth and fertility, cover vegetation and create hard-pan surfaces that do not support vegetation normally found in the local environment. These impacts are to the source area environment, but source areas can also experience the other impacts summarized below, as sand and dust may move over very short distances, making the source-destination distinction less relevant when SDS occur.

Financial – All the aforementioned impacts have direct or indirect impacts on finances, whether from loss of employment due to damage irrigation systems, loss of production for the same reason, increased operating costs due to a need to clean up after an SDS event, or increased operating and maintenance costs for infrastructure. Under ideal conditions, all the financial impacts of SDS would be translated into clearly defined cost data, leading to a clear costing of these impacts. Middleton (2017b) and Tozer and Leys (2013) provide overviews of SDS cost issues.

7 As viewed during a field trip organized as part off the International Conference on Combating Sand and Dust Storms, Tehran, Iran. 3–5 July 2017.

8 Tourists can also intentionally visit SDS-impacted areas, such as the Dust Bowl in the United States.

9 SDS are often associated with low humidity. While entrained dust and sand does affect air density, the lack of heat-retaining moisture in the air can lead to a pattern of warm days due to direct heating from the sun and cool nights since the dry air retains little heat.

However, this is likely possible in only a few cases where good quality reporting on the range of impacts is available (Tozer and Leys, 2013). See **chapter 6** for more on the financial aspects of SDS.

Governance – These impacts are generally associated with the extent to which a governance system (including political systems and politics) respond to SDS, as single events or as a type of hazard. Disaster risk governance systems that have strong capacity to address SDS will reduce the impacts noted above, with weak governance having the opposite impact. For SDS as a transboundary hazard, governance impacts include consideration of national as well as transnational capacities, generally in the form of cooperation and collaboration, as well as the role that regional and international organizations are engaged in to assist governments with managing SDS. More on risk governance can be found in Gall et al. (2014), while Hemachandraa et al. (2017) discuss the role of women in disaster risk governance.

Health – Entrained dust, in particular where particles are smaller than 10 microns, can enter lungs and smaller 2.5 microns can reach deep into lung tissue (UNEP et al., 2016). The result can be severe breathing problems for at-risk populations (for example people with chronic lung problems), as well as the potential for disease transmission (Goodyear, 2014) or the transportation of toxic chemicals or radiation, for instance reported for the Aral Sea region (Columbia University, 2008). Other direct health impacts include eye and circulation problems, as well as illnesses from contaminated water supplies. Vulnerability to health impacts appears to first impact those with pre-existing health conditions (for example asthma) and then, as SDS conditions become more severe, the larger population in an SDS-impacted location. (See Goudie, 2014; Khaniabadi et al., 2017; Al-Hemoud et al., 2018; and Middleton, 2017b.) See **chapter 11** for more details on health and SDS.

Infrastructure – SDS events can close roads with blowing sand or, under the right conditions, shift the ballast of roads. Blowing sand and moving sand dunes (often associated in space and time) can cover buildings and other infrastructure and incur recurrent costs for regular sand clearance.

The movement of sand and large quantities of dust can fill irrigation and water supply channels, reducing effectiveness and requiring increased maintenance costs and also affecting water quality (which can lead to health issues, as well). Dust can impact solar panel efficiency (Al-Dousari et al., 2019) and microwave and radio transmission effectiveness. Blowing sand can pit glass on solar panels and other surfaces, leading to reduced effectiveness and higher operating costs. (See Middleton, 2017b and Baddock et al., 2013.)

Livelihoods – Livelihoods impacts are a broad category that can encompass economic, health, infrastructure and financial impacts but generally focus predominantly on SDS impacts at the individual and household levels. These impacts include lost or reduced income due to SDS damage to crops or reduced work opportunities, reduced food security due to these and other impacts, SDS-related health cost burdens on individuals and families and other impacts that may be noted at the individual or household levels, but not well captured elsewhere.

Social – Health and other impacts can have a knock-on effect on individuals, extended families and society in general. These impacts can range from the stress of dusty conditions or blowing sand to caring for family members who experience health problems during an SDS event. Social systems are important in reducing or mitigating impacts and the severity of impacts often reflects how well social systems deal with potential disasters.

Transportation – SDS can lead to reduced visibility, leading to transport accidents (Tobar and Wilkinson, 1991; Associated Press, 1991). Even relatively low densities of atmospheric dust have contributed to aircraft accidents. Note that transport impacts can be very local (blowing dust due to the ploughing of fields) or regional (dusty conditions leading to airport closures). (See Baddock et al., 2013, for a more detailed discussion of SDS and the transport sector.)

4.4 Assessing vulnerability to SDS

Defining a process for assessing vulnerability to SDS needs to firstly consider the availability and reliability of data on weather conditions (including air quality), health status, economic impacts and environmental conditions, and whether the data are consistent spatially and over time. Where SDS-affected locations have good data, in the sense of reliability and consistency, a range of statistical methods can be used to assess impacts and differentiate impacts by levels of exposure to a single SDS event, or the cumulative impact of several events. **Chapter 7** provides an SDS-focused process to assess vulnerability where data availability or quality is not a critical issue.

It is also possible, and preferred as a decision-making tool, to define SDS impacts in terms of value lost. Such economic impact assessments are often used after a disaster to define the cost of the disaster. As part of a risk assessment, projecting economic loss from future events can be very useful in identifying where investments in risk reduction will be most effective. Economic-loss-based risk assessment and updates can be extremely useful in measuring progress in reducing losses and the changing nature of risk over time.

Chapter 6 provides a process for assessing the economic impact of SDS. Where data are available, economic damage and loss assessment procedures can be used, with such assessments often being carried out, in one form or another, post disaster (see Global Facility for Disaster Reduction and Recovery, n.d.).

However, a challenge arises when the assessment of SDS vulnerability includes locations where data are not considered fully reliable or consistent for all the impacted areas and populations. This situation, in addition to missing data sets for some locations covered in an assessment, will yield results that over- or understate vulnerabilities, or miss them altogether. Such results limit the utility of an assessment in defining and prioritizing actions to reduce individual and societal vulnerability to SDS.
Clearly, some SDS-affected locations have access to reliable and consistent data. However, to compare SDS impacts at a regional scale, between nations or between adjoining parts of neighbouring nations, the least reliable or consistent sources of data need to be considered the norm upon which the assessment process is based. Issues with data reliability and consistency and the availability of sex- and age-disaggregated data are noted for several large parts of the SDS-affected areas globally.

A common approach to the need for reliable and consistent data is to create proxy indicators of vulnerability using the best available data. One example is associating the level of poverty with increased vulnerability under the assumption that poorer people will have fewer means to manage a hazard.

While such logical justifications for selecting indicators from limited data sets may appear sound, the process faces three problems:

- The underlying data, for instance on poverty, may have the same reliability-consistency issues as for data more directly related to SDS vulnerability.
- There may be no clear evidence to back the logical justification, in part because of the lack of reliable or consistent data.
- The process of combining different indicators may not address the issue that the indicators themselves may not be comparable. For instance, does it make sense to combine poverty levels and urban environmental conditions and poverty levels and rural environmental conditions, given that urban and rural environments are very different?

Working through these problems, for an assessment process that needs to consider local to aggregate global SDS vulnerability, presents significant challenges that are unlikely to be resolved in the near future. (See **chapter 7** on data used for a GIS-based system to assess vulnerability.)

The alternative is to turn to research on the sociology of hazards and use the perception of vulnerability to measure and compare vulnerability.
The use of perceptions in understanding vulnerability and risk is well established (see Slovic,1987, and Pidgeon et al., 2003).

In practice, using perceptions to assess vulnerability is reasonable because:

- data can be collected in ways that are reliable and consistent spatially and over time
- these data can be analysed using normal quantitative methods, and
- the process can incorporate general perceptions of SDS vulnerability from those at risk and potentially more informed perceptions from topical experts

Evidence indicates that individuals act to address hazards based on their perceptions of the significance (threat) of a hazard. Knowing how individuals, and groups of individuals in a location, perceive a hazard, and how these perceptions differ due to gender, age, social status and so on, is important to understanding how individuals will act to address the hazard. This, in turn, helps define the needs for education about the hazard before people will be being willing to act to reduce vulnerability.

Data on respective perceptions of SDS vulnerability are most easily collected through a questionnaire administered to individuals or groups. Recent advances in data collection have significantly reduced the difficulty and time needed to collect and analyse questionnaire-generated data.[10]

As noted, individuals use their perceptions as a way of defining their vulnerability to hazards. Meanwhile, an expert's understanding of vulnerability is based on research and data, but also on their professional experience – their perceptions – gained over time. Thus, a doctor treating breathing problems will base their assessment of vulnerability not only on research results and recorded health data from patients, but also on their experience in treating patients with similar conditions. This combination of data-based analysis and experience significantly expands an expert's ability to understand and define vulnerability.

Using expert understanding of vulnerability presents two challenges:

- No single expert will have a full understanding of all aspects of vulnerability.
- Individual experts may frame their understanding in ways that are different from other experts in the same field.

The first challenge is addressed by involving a range of experts from different fields (for example health, weather, agriculture, social services, economics, emergency management, transport, gender) in the assessment process. Within reason, the more – and the more diverse – the experts involved, the broader and deeper the common understanding of vulnerability to SDS that will develop.

The selection of experts should reflect the scale of the assessment. For example, experts with a knowledge of vulnerability due to changes in environmental conditions within one part of a country may not be appropriate for an assessment with a transnational focus on vulnerabilities.

10 The KoBoToolbox is a commonly used software package for the collection and analysis of data collected through questionnaires. See https://www.kobotoolbox.org/.

The second challenge is addressed by providing those involved in the assessment with a structured set of definitions of levels of vulnerability. This serves to frame discussions and decisions by experts so that, to a significant degree, expert understanding of vulnerability generates similar assessment results across different locations and scales of assessment. This allows assessment results to be compared across space and scale – a significant advantage given the global nature of SDS events.

The use of expert understanding in a structured assessment framework is an adaptation of the Delphi method, with a focus on gaining a consensus of experts on levels of vulnerability.

Background on the Delphi method, and its more complex applications, can be found in Cuhls (n.d.). A similar method for climate hazards is described in the CAMP Alatoo and UNDP Central Asia Climate Risk Management Program (2013a, and 2013b).

Framing vulnerability

The analytical framework to be used by experts in assessing vulnerability is drawn from the Sustainable Livelihoods Framework (SLF) (United Kingdom of Great Britain and Northern Ireland, 1999) and the identification of types of capital that can be affected by a hazard. An advantage of using the SLF is that it covers a broad range of factors which can define vulnerability and so provides

a broad base for understanding the nature of vulnerability and where actions to reduce vulnerability can be targeted. The Sustainable Livelihoods Framework encompasses the categories of impacts already set out in **chapter 4.3.2**.

The six types of capital used to assess vulnerability are:

1. **human**, principally human health in recognition of the health impacts of SDS, including fatalities due to SDS-related transport or other accidents
2. **natural**, broadly, the natural environment (for example ecology, natural resources) which can be affected by, but also contribute to, SDS in the case of locations that are both sources of SDS and impacted by SDS
3. **physical**, including infrastructure (such as roads and irrigation, power, communications and other lifeline systems) and assets needed for work or employment, including seeds, tools and equipment that can be affected by SDS
4. **financial**, covering the income, credit and savings available to places vulnerable to SDS to pursue normal activities and cover extraordinary costs, where these assets can be lost or reduced by an SDS event. Note that the cost of addressing SDS impacts can reduce savings even as income remains unaffected.
5. **social**, covering the personal connections (for example extended family, associations, and other support mechanisms) that play a significant role in reducing or exacerbating vulnerability to SDS
6. **political**, the governance systems that can reduce or increase vulnerability to SDS

The first five types of capital are adapted from the Department for International Development (United Kingdom of Great Britain and Northern Ireland, 1999) and Twigg (2001). Political capital is not included in the standard SLF but it is included in the SDS assessment process to capture government engagement in addressing vulnerability. These six capitals largely cover the focus of the SDS risk assessment on the environment, economy and industry, human health and socio-politics.

Table 4. Scaling vulnerability to sand and dust storms provides descriptive indicators for various levels of SDS vulnerability for each of the six capitals, ranging from insignificant to extreme.

While the expert-based assessment draws primarily on the participating experts' understanding of the impacts of SDS, reference should be made, where possible, to existing reliable and consistent data sets. This reference to available data supports a deeper understanding of the nature of vulnerability and can make the selection of one descriptor of vulnerability over another easier and clearer.

Elaborating on what is covered under each capital in terms of vulnerability to SDS based on local conditions, for instance including solar panels under the physical capital group, can help with developing the expert consensus on levels of vulnerability. In other words, the more information to inform expert decision-making, the better.

SDS impacts are not consistent across all age groups and physical conditions. As a result, the expert-based assessment process should first cover the general population vulnerable to SDS within an area to be assessed. Moreover, on the surface, the SLF framework does not differentiate between women, men, boys or girls, age or disability. As a result, gender, age and disability analysis should be used as part of the scaling of vulnerability to better understand the vulnerabilities and capacities.

Consequently, the assessment process should then be redone for specific groups considered to have specific or heightened vulnerabilities to SDS, such as girls, women, children, older persons or those with lung or circulation-related health conditions, for example. This leads to results that help understand the depth and breadth of vulnerability to SDS across the at-risk population.


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Table 4. Scaling vulnerability to sand and dust storms

Type of capital	Level of vulnerability				
	Insignificant	Low	Medium	High	Extreme
Human, focused on human health	No negative short- or long-term outcomes for health indicated.	Temporary negative short-term health outcomes for part of general population; no deaths.	Limited, short-term negative health conditions for majority of the target population; one or more deaths attributed directly to dust or sand.	Large numbers of target population experiencing negative short- to long-term health impacts, with several deaths directly attributed to sand or dust.	Widespread health impacts and fatalities above 1:10,000/day in affected population.*
Physical, focused on infrastructure and physical assets needed for work or other purposes	No vulnerability of physical capital noted.	Limited, local, short-term damage to limited segments of physical capital.	Broad but short-term (less than a week) damage to physical capital.	General, lasting (more than a month) damage to physical capital.	Destruction of physical capital, limiting the use of infrastructure and buildings and the operations of irrigation systems and affecting resources for crop production or animal husbandry.
Financial, focused on income, savings or access to credit	No loss of income or financial resources.	Temporary loss of income due to unemployment or other reasons (for example no rental income), reduction in savings, increased reliance on credit, or a combination of all three.	Loss of income due to unemployment or other reasons (for example no rental income) beyond a month, reduction of savings for more than a month, reliance on credit or a combination of all three.	Loss of work for more than six months and reliance on savings or credit to meet needs.	Near-total loss of income and savings and no access to credit.
Social, focused on support available from family, friends and other social networks	Support from social network not needed.	Limited support from social network required.	Significant support from social network required, but for only a limited period (months).	Significant support from social network required for an extended period (beyond several months).	Total reliance on social network to meet needs.
Natural, focused on the state of the natural environment and natural resources	No damage beyond levels normally experienced.	Short-term reduced use of natural resources to meet basic needs.	Reduced use of (access to) natural resources needed to meet normal needs for 3–4 months.	Extended reduced access to natural resources needed to meet normal needs.	No access to natural resources due to damage to natural systems.
Political, focused on capacity of governance systems to address threats from SDS	Government response addresses threat.	Government response effective but with limited gaps.	Government engagement with SDS, but significant gaps.	Very limited government engagement with SDS.	No government engagement with SDS.

Note: The 1:10,000 fatalities to population threshold is generally used as the marker for a transition from a normal level of fatalities to those indicating a disaster. For more details on disaster-related fatality rates, see Checchi and Roberts, 2005.

4.5 Conclusions

This chapter has reviewed the nature of SDS as a hazard and defined SDS characteristics that should be considered when defining the scale and impact of these events. A typology of SDS events has been provided based on the characteristics of different SDS events. The typology is intended to make SDS classification clearer for SDS risk assessment, considering that those performing the assessments will not be SDS experts.

The chapter has reviewed the nature of vulnerability and how it is affected by SDS. A table for **Scaling vulnerability to sand and dust storms** has been developed based on a modification of the Sustainable Livelihoods Framework (SLF) (United Kingdom of Great Britain and Northern Ireland, 1999). This vulnerability scaling provides those conducting SDS risk assessments with a way of assessing vulnerability in data-poor conditions, or where data are inconsistent between locations. The vulnerability assessment process is also linked to the GIS Vulnerability Mapping process found in **chapter 7**.

The materials covered in the chapter, and the typology and vulnerability scaling information, provide a straightforward foundation for assessing the risks posed by SDS. Specific approaches to risk assessment are covered in **chapter 5**.

4.6 Web-based resources

- Environment and Disaster Management – http://envirodm.org/
- Environmental Emergencies Centre – http://www.eecentre.org/
- Environmental Peacebuilding – https://postconflict.unep.ch/publications/UNEP_ECP_PBR01_highvalue.pdf
- The Health and Environment Linkages Initiative (HELI) – http://www.who.int/heli/impacts/hiabrief/en/
- ReliefWeb – https://reliefweb.int/
- WMO, Environment web page – https://public.wmo.int/en/our-mandate/focus-areas/environment/sand-and-dust-storm/sand-and-dust-storm-warnings
- WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) – https://www.wmo.int/pages/prog/arep/wwrp/new/SDS_WAS_background.html
- Convention on Biological Diversity, What is impact assessment? – https://www.cbd.int/impact/whatis.shtml

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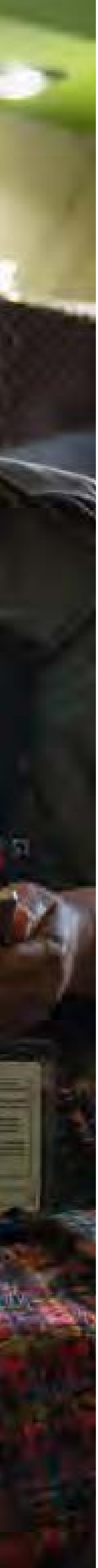


5. Sand and dust storms risk assessment framework

Chapter overview

This chapter reviews the conceptual approach to assessing SDS risk and provides two methods for assessing this risk: one using expert opinions and the second using the perceptions of those who are at risk from SDS. Each of these methods is described in a step-by-step process (including assessment forms and questionnaires) and includes samples of assessment outputs. Also discussed are how to assign confidence to results; the consideration of climate, environment and population changes; and assessing impacts in source areas.

5.1 Framing the SDS risk assessment process

The risk assessment process, as described in **chapter 4**, brings information on SDS hazards and vulnerabilities to this hazard together to define risk for different return periods for different types of SDS events. The generalized process for an SDS risk assessment is set out in **Table 5**, with specific procedures for survey and expert-based assessments covered in this chapter.

Any assessment report should include a summary of the SDS situation being assessed as part of Task 2, alongside background information on the assessment area, typical types of SDS experienced and other types of hazards or disasters that may occur. The report should note whether the assessment location is a major source area for SDS.

Table 5. Framing the sand and dust storm risk assessment process

#	Task	Notes
1	Identify and document a reason for the assessment.	If possible, the assessment should be linked to SDS risk mitigation in a specific area or location.
2	Define the spatial area of the assessment and whether the assessment focuses on a source area, an impact area or both, for combined source/impact locations.	Note that for some SDS, source and impact areas can overlap, and local sourcing may be significant (for example Type One). In general, the smaller the assessment area, the more precise the risk assessment. If the source area is some distance from the impact area, a short description of the origin and movement of the SDS should be included. Identify whether the sand and dust is expected to have any contamination or be a transmission mode for a disease.
3	Identify the SDS types from **Table 2** to be covered in the assessment.	For areas affected by more than one type of SDS, the risk assessment process treats each type of SDS separately, with comparable results.
4	Assign return periods to the SDS being assessed.	See **chapter 4.2.3** on return periods. Return periods can be defined using weather data from one or more stations in the assessment area, and the more data the better.
5	Collect data on vulnerability to SDS and other factors.	Choose whether to use the questionnaire or expert approaches to assess vulnerability (see **chapters 5.5** and **5.6**). The assessment should include the analysis of existing vulnerabilities and capacities specific to girls, women, boys and men and consider age and disability factors.
6	Repeat steps 2 to 4 for each type of SDS that can affect the spatial area covered by the assessment.	
7	Analyse results by SDS type and return period.	Results can be compared by return period across type, but most likely by type for return periods. Location, gender, age, disability, health conditions, social status and economic factors should form part of the analysis, with these factors included in the reporting of results.

8	Develop a report covering the assessment results.	The report should explain the reason for the assessment and the assessment process and should detail results and their implications for, for instance, risk reduction.
9	Validate the results.	The assessment results should be shared with, and validated by, at the least a representative group of the populations covered by the risk assessment. Comments from the validation should be incorporated into any report and used to improve the assessment process, and in particular, the vulnerability assessment.

5.2 Incorporating SDS source-area related risks

Many, but not all, locations impacted by SDS also contribute sand and dust that circulates in an SDS event. Both assessment methods described in this chapter can incorporate SDS source area risks (for example erosion associated with dust generation or movement of sand due to wind) into the assessment results.

For the survey-based assessment, source area risks are included by asking about the perceived and observed impacts of SDS events on the local environment. For instance, do SDS events remove topsoil, reducing locations where crops can be grown, or does blowing sand and dust during SDS events fill in irrigation canals? In the questionnaire in **Table 6**, questions 31 and 33 touch on source area impacts. Additional questions can be added to expand on specific source area concerns noted for where the assessment is taking place.

For the expert assessment, conditions related to source area risks can be included within the background information and location-specific questions can be posed to the experts as part of the assessment process. The extent to which source area risks are incorporated into the expert assessment will depend on the level of pre-assessment research available.

Where no sand or dust is taken up in an SDS event (for example in Barbados), the source of sand and dust would be considered only if this sand or dust had an impact on the population and locations being assessed. This would be the case, or instance, for dust containing chemical contaminates that put human health at risk.

Information on sand and dust source areas may be very useful in an assessment, and in identifying ways to reduce risk. However, tracking the source of sand and dust, and its chemical or biological characteristics, can be complicated. The costs and time involved in developing a detailed assessment of source area and sand or dust characteristics may not be feasible with the resources typically available for risk assessments. If this information is to be used, it needs to be collected before an assessment and to feed into the formulation of SDS characteristics that are used in defining the scope and questions used in the survey assessment or as input for experts in the expert assessment process. See **Box 6** for more information on assessing source areas.

Box 6. Assessing source areas

Identifying source areas can be important to determining the impact that sand or dust may have on the at-risk population. A challenge exists in that SDS source areas are quite diverse, ranging from large dry lake beds to a few square kilometres of ploughed land. As a result, the assessment design should consider both (1) the nature of the source area as a contributor of hazards (for example disease agents or radiation in dust) and (2) the extent to which some or all of the sand and dust in a storm comes from a local or distant source. Where some or all of the sand and dust in a storm comes from a source at the location being assessed, this factor should be included in the risk assessment.

A somewhat differently focused assessment would involve looking at the impact of sand or dust coming from a specific area on that area alone. In this case, either the survey or expert procedures could be used, but the focus of questions and discussions would be directed towards the impact of wind and other factors on the physical, social and economic environment where these factors are present.

For instance, if SDS events cause a loss of top soil affecting crop production, then the assessment would focus on these impacts to understand the nature of the hazard, vulnerabilities and resulting risks.

In most cases, these source area impacts would be part of the overall risk assessment. However, in some locations the source area impacts may be greater or more significant than other impacts or may be more significant in terms of overall or specific risk reduction. In these cases, a risk assessment focusing on source area impacts alone may be justified.

5.3 Comparing assessment processes

Ideally, both the survey and expert assessments discussed below are conducted for the same locations. This provides a basis for comparing results and gaining a deeper understanding of SDS risk.

Advantages of the survey approach include obtaining more direct information on impacts from those affected by SDS, a clearer understanding of how these may differ across age, gender and social groupings, and results that can be presented on a per capita basis (for example "x per cent of the total population indicated y impact").

The survey approach also identifies the most significant concerns about SDS among the surveyed populations; an important consideration when selecting risk reduction options. At the same time, surveys can be expensive, require time (weeks to months depending on their scale) and may yield variable (and possibly inconsistent) results for different locations surveyed, reflecting localized SDS impacts and risks.

Advantages of the expert approach include time (for example a two-day assessment workshop with 15 experts), cost and results that are based, in part, on research and synergized from expert opinions developed over years and across disciplines. In general, expert assessment results carry greater weight with decision makers and can consider multiple hazard and impact interactions across medium- to large-scale SDS situations.

Challenges with the expert assessment include that the results can be general in nature and not applicable to each location within an impact area. Results can also be strongly influenced by the technical expertise of experts involved, for example a preponderance of health experts participating in an assessment will skew results towards SDS health issues.

Broadly speaking:

- field survey-based assessments are most useful in identifying SDS risk issues that can be addressed at the project level
- expert assessment results focus more on policy outcomes

However, field surveys can also be used to frame policy, particularly when used to explain the impacts of SDS on at-risk individuals and as input into the expert assessment process.

Either assessment procedure, when used in the same way for different locations, can be used to compare SDS impacts and risks between assessed locations. To ensure that these comparisons are appropriate, the scale (number of persons covered by surveys, or spatial area covered by expert assessments) should be similar.

Box 7. Considering climate, environment and population changes

Risk assessments are used as inputs into future actions to reduce the risk of negative impacts. It is important to consider whether changes to the climate, the overall environment (both prime elements in the generation of SDS) or at-risk populations will change the risk.

With changes to the climate, the issue to be researched is whether the projected changes will change weather and weather patterns in such a way as to increase or decrease the likelihood or intensity of SDS events. Similarly, will changes to the environment, related to climate change, changing land use or other factors, affect the likelihood and frequency of SDS events? For at-risk populations, will the change in the number, composition (for example increased numbers of older persons) or other factors change the impact of SDS events? Unfortunately, how these factors combine and affect – or are affected by – SDS are not global or uniform.

In the case of the expert-based assessment (see **chapter 5.6**), background information collected as part of the assessment work can be used to summarize projected impacts of changes to the climate, environment and at-risk populations. These expected changes can be incorporated into the assessment process. For instance, once the rating process is complete, the experts can be asked how projected changes in the climate, environment or at-risk populations could change the results.

Incorporating possible changes to the climate, environment or at-risk populations into the survey-based assessment (see **chapter 5.5**) is problematic as a respondent's recall of long-term changes is often limited. In this case, the team conducting the assessment should add a research-based prospective analysis of how the survey results may change based on projected changes to the climate, environment or at-risk populations.

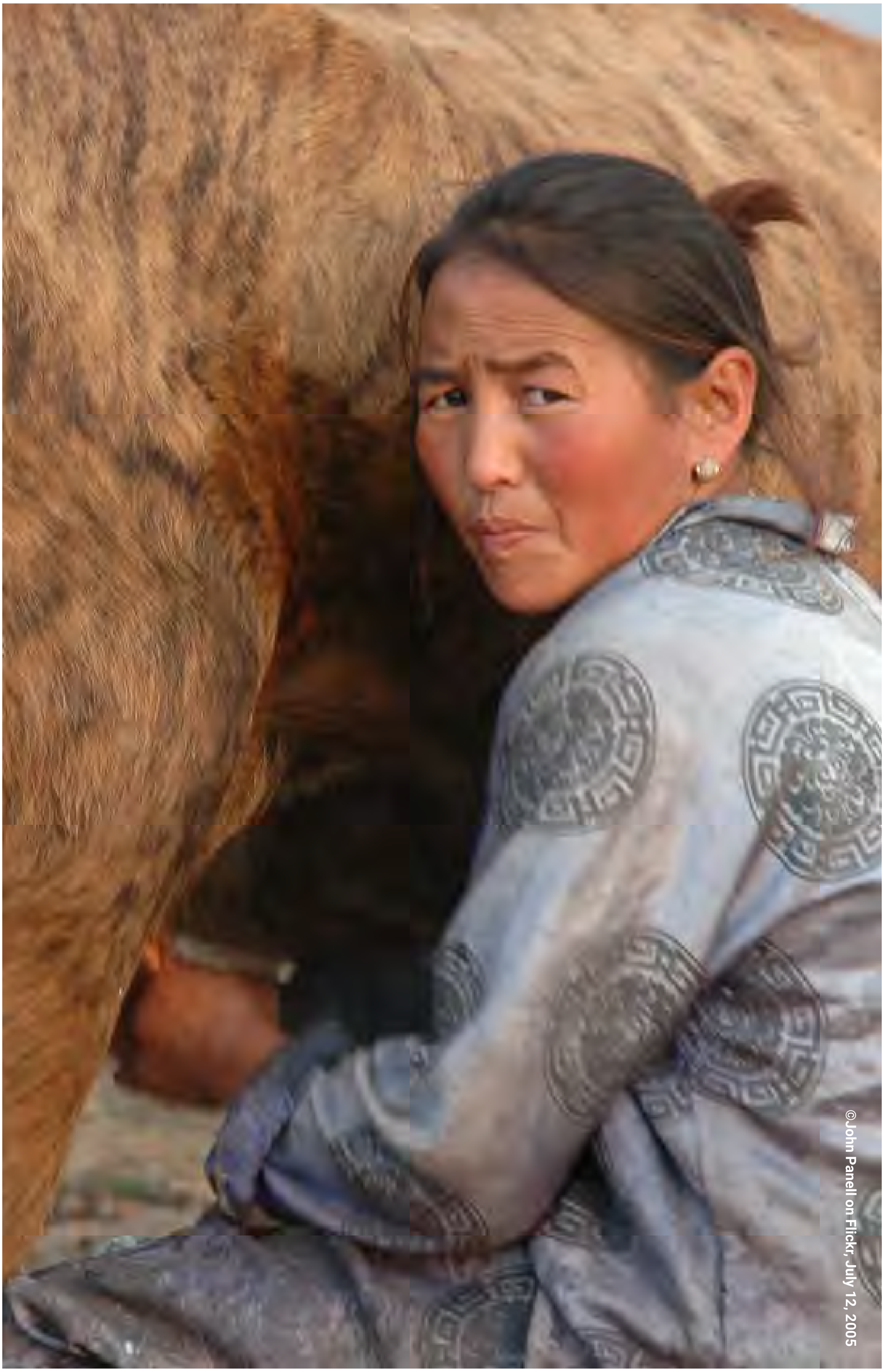
5.4 Scaling assessment results

The survey assessment process uses statistical methods to compare the data collected with the overall population in the assessment target area. This is particularly useful in determining the number of persons affected by a certain aspect of an SDS event. In turn, this scaling of impact can identify where the most severe impacts occur and identify specific target populations and impacts for risk reduction. This is why survey-based assessments are useful for project-level interventions.

The expert assessment process is more specific to the impact and risks for a spatial area affected and is less specific to affected populations, and thus, as noted, for policy-level considerations. However, because the expert assessment process considers impacts on, and risks to, specific populations (for example children and women), it is possible to broadly project the number of persons at risk from a specific aspect of an SDS event based on the general demographics of the area being assessed.

When comparing the same SDS risks for two different populations, the population with the greatest number of persons at risk is considered to be at greater overall risk. In other words, risks being equal, the more people affected, the greater the overall risk.

It is possible to use statistical methods to compare the relative significance of different SDS risks, within or between populations, for survey assessments. For the expert assessment process, the comparison of risks is possible by comparing the risk ratings. However, as the expert process does not incorporate demographic data in the same way that the survey process does, comparison between risks and populations are indicative based on the agreed judgements of the experts involved. In this case, an assessment of confidence in the results is needed (see **chapter 5.7**).



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5.5 Survey-based SDS assessment process

This section describes the steps to develop, implement and analyse results from an assessment of perceptions of risk posed by SDS based on the survey process framed in **chapter 5.1** and **Table 5**, which is generally based on a questionnaire or question guide. Note that the assessment process first considers perceptions of vulnerability, before combining these perceptions with hazard information to generate a risk assessment.

This process involves a trade-off between precision on return periods (explained below) and local knowledge of vulnerabilities to SDS. The results are most appropriate for considering the risk posed by more frequent events, but they can capture vulnerability to a less frequent, but more severe event, if the assessment is conducted soon after this event.

The survey process is relatively quick and simple and can be repeated at regular intervals to develop a more detailed overall longitudinal understanding of SDS risk. As the same procedure would be used for each survey, results would be comparable over time and across locations.

Step one – Define why the assessment is needed

An assessment of SDS risk should have a clear purpose and, preferably, a role in SDS risk reduction.

Step two – Define the location for the assessment

The selected geographic location for the assessment should be well defined to avoid later confusion as to where actual surveys will take place.

Step three – Collect background data

These data should include demographic and socio-economic information that can be used to describe the assessed populations, the economy and infrastructure. Data on past SDS events and other hazards and disasters should be collected for reference.

The SDS data will provide the basis for defining SDS types and return periods (see **chapter 2**). Key informant interviews and an analysis of gender, age, disability and other factors defining the at-risk group should also be used to understand the physical, social and economic nature of the survey locations.

Step four – Design the survey

Normal procedures for using field survey questionnaires should be used to design the survey work, including the sample frame, confidence levels and survey procedures. Decide whether the survey will be conducted on an individual basis or with focus groups or key informants or using a combination of methods.

A commercial company can be hired to design and undertake the survey and conduct the analysis. It is also possible to work with NGOs or other segments of civil society to develop and conduct the SDS survey. Finally, government institutions, for instance statistics offices, may have the capacity to undertake the survey work using their own resources or they may be able to commission it.

In general, the larger a survey (larger sample size), the greater the cost. The cost–results trade-off is a core part of the design process. Surveys at the level of villages in an assessment area of 100 villages will be more expensive and time-consuming than surveys at the district level for 10 districts. The total population covered may be the same (the 100 villages are located in the 10 districts), but the results will be less specific if the scale of the assessment focuses on the 10 districts.

Assessment scale is important when comparing results across assessments. An assessment at the level of 10 districts cannot be compared to an assessment covering 100 villages within a district until the results from the latter are aggregated to the district level. This aggregation process will lead to a reduction in spatial specificity in terms of vulnerabilities and results.

Survey design should ensure that sampling covers all segments of a society and that results can be disaggregated by gender, age and physical capacities.
Deciding who will conduct the survey and how they will do so will define the organization and size of the survey team and the level of management and support required. Work on survey design would cover survey methods, team composition, logistics, etc. These details are not covered here as they are standard for questionnaire-based surveys.

Step five – Develop a questionnaire and plan the field survey

A model questionnaire for an assessment of perceived vulnerabilities to SDS is provided in **chapter 5.9**. This questionnaire would need to be adapted for each area being assessed to reflect local environmental or social issues, but the core questions and scaling of answers should remain the same to enable comparison of survey results across assessments. As a matter of normal practice, any questionnaire should be tested before general use.

The field survey work should be planned out in detail once the questionnaire has been developed. The planning builds on the survey design process and should include staffing and job descriptions, training of surveyors, written procedures for selecting those to be interviewed, printing or otherwise providing questionnaires, quality control and logistics, at a minimum. Online resources or the services of a professional field survey expert or company can be used in the planning process. As a general rule, academic standards should be incorporated into the field survey plan.

In some cases, survey data can be collected using software that uses the Internet to automatically report the data collected into a database for analysis.[1] The use of data-collection software should be integrated into the questionnaire and field survey design process.

Step six – Secure authorization to conduct the survey

Countries and organizations generally have protocols or review panels that should approve a survey or other public data collection process.

Step seven – Conduct the survey

This step involves implementing the plan developed in **Step four**.

Step eight – Analyse and report on the data

Basic analysis of the survey results should be carried out using standard statistical packages to compile and present simple results (for example frequency, number of responses) for each question. The questions on SDS experienced by those interviewed should be linked to the six types of SDS set out in **Table 2**. **Sand and dust storm hazard typology**, which should be included in the analysis process by totalling the number of each type of SDS.

Different types of analysis can then be performed. First, responses by the whole surveyed population can be presented in terms of the perceived severity of each type of SDS reported. This analysis can be presented as percentages of total number of respondents.

Second, analysis can compare the severity responses by type of SDS using disaggregated data on gender, age, occupation, economic group or other criteria collected through the questionnaire. In each case, the analysis should be done by category, for instance perceived impact on health, agriculture, travel, infrastructure, social connections, or warning, as set out in the questionnaire. The result provides an impact category-by-category analysis identifying the impacts that are perceived as most severe for each type of SDS.

1 The KoBoToolbox is a commonly used software package for the collection and analysis of data collected through questionnaires. See https://www.kobotoolbox.org/.

Results should be reported as text, with the use of charts and maps to facilitate understanding. See **Box 8** for a sample chapter of a simple report-out example.[2] Normal academic-level procedures for presenting data and reporting results should be followed, including reporting on the validity of statistical results.[3]

Step nine – Disseminate and validate results

As per Task 9 of the **Framework** (**Table 5**), results should be validated by sharing them with those affected by SDS and living in the assessment area. Dissemination products include reports, press releases, journal articles and public events.

Additional considerations

In general, perception surveys will not allow for an assessment of multiple return periods but they can cover different types of SDS. In most cases, the survey will capture perceptions based on the most recent events, which may be more severe than average events. By dating these most recent events, it is possible to link them to observed weather data and classify them in terms of statistical return periods.

Perception surveys can face difficulties in trying to align participant descriptions of an SDS event with standard names or the typology (**Table 2**). To address this challenge, pictures of different types of SDS can be prepared in advance and used by the participants to select the type of SDS most like the one that they describe. This process can improve the accuracy of the assessment process and the link between SDS recorded at weather stations and SDS reported by the survey participants.

It is also important to consider when to conduct a survey. A survey during the normal SDS season may yield perceptions skewed by an ongoing or most recent SDS event. Thus, where possible, surveys should be conducted outside normal SDS periods. The selected area should be well defined to avoid later confusion as to where actual surveys will take place.

Reporting on results should include a description of the SDS issue being assessed and other background on the assessed location.

2 The text provided is a snippet and would be longer in a real report.

3 The level of confidence in results should be based on standard statistical analysis and not on the process set out in **chapter 5.7**.

Box 8. Sample simple survey results report-out – health effects

A survey of 240 respondents (46 per cent male) was conducted in Zira Department (population 5,632; 52 per cent female) to assess the perceived impact of SDS on health. The data are presented in the chart below. The median per capita income for the district is US$ 3,760, the main occupation is semi-mechanized farming (wheat, maize) and the poverty rate is 15 per cent.

For Type Five SDS (high intensity-very small area), 83 per cent of respondents (56 per cent female) reported important or very severe health effects. Note that the survey area is subject to Type Five SDS due to the ploughing of loess-type soils during the spring windy period. For Type One SDS (high intensity-large area), 52 per cent (62 per cent female) reported important or severe effects. Few respondents indicated more than limited effects from Type Two or Six SDS (low or moderate intensity-large area and low intensity-very large area).

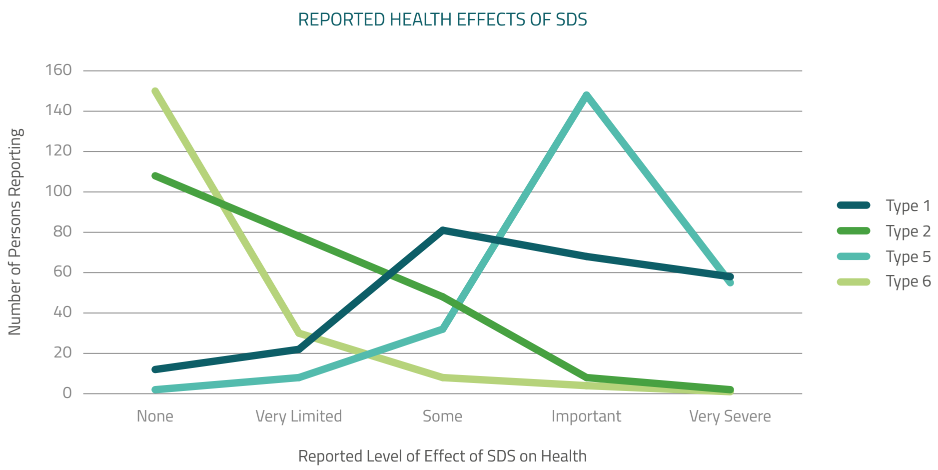
The Type Five important and severe health effects reported during the survey included:

- asthma (mentioned 46 times)
- fever following SDS events (mentioned 142 times)
- breathing problems requiring hospitalization (mentioned 74 times)
- high blood pressure and circulation problems (mentioned 73 times)
- eye irritations (mentioned 153 times)
- general difficulty in breathing, not requiring hospitalization (65 times)

Older persons and young children were reported to be the most affected. No fatalities were reported among the survey population.

Based on weather data from Zira airport, Type One storms have a return period of twice a year, Type Two events twice a year, Type Five events three times a year and Type Six events once a year. Type Three and Four events were not reported by respondents or identified based on airport data.

Figure 15. Reported health effects of sand and dust storms



Box 9. Including gender and age in the assessment

Good practice for conducting and reporting on assessments calls for gender and age to be an integral part of both processes. Including age as a factor in data collection and analysis helps with understanding the differential impact that sand and dust can have on young children and older persons. Incorporating gender assists in understanding how impacts can differ within a population where different gender groups may live and operate in different physical and social conditions.

For survey-based assessments (see **chapter 5.5**):

Gender is included by:

1. Ensuring that assessment teams and field assessment teams are gender-balanced, as far as possible
2. Collecting data on gender – of the individuals contacted, focus group meeting members and the general population – as part of the assessment process
3. Analysing data from a gender perspective to identify practical and strategic gender impacts
4. Disaggregating data analysis, results and conclusions

Age is included by:

1. Collecting information on the age of respondents. This information is usually divided into three groups: young children (younger than 60 months), older persons (at or over the local age of retirement, usually between 60 and 65) and the remaining age group (between 6 and 60 years). The 6 to 60 age group can be further segmented if justified by expected SDS impacts or other factors. The basis for segmenting people into specific age groups should be provided as part of the assessment reporting.
2. Disaggregating data analysis, results and conclusions by designated age group.

Common good practice is to also disaggregate impacts by age groups and gender, for example, SDS impacts on older women.

For the expert-based assessment (see **chapter 5.6**), gender and age are included by repeating the assessment process and asking how the assessment results would change for specific age groups, by gender, or by a combination of both (for example girls). As with the survey-based assessment:

- Expert teams should be gender-balanced as far as possible, and supported by dedicated gender expertise where available.
- Results should be disaggregated by age, gender and, where relevant, age/gender combinations.

5.6 Expert-based sand and dust storms assessment process

Box 10. Expert-based assessment process overview

The expert-based process involves:

1. Selecting an SDS type from **Table 2. Sand and dust storm hazard typology**, with reference to background materials on SDS for the locations being assessed.
2. Having the experts review **Table 4. Scaling vulnerability to sand and dust storms** and agree on a score for each type of capital that most accurately reflects the effect of the SDS event on the overall population covered in the assessment. The Insignificant, Low, Medium, High and Extreme scores can be converted into numbers (1 to 5) for ease of reference. If relevant, notations can be added to the scoring to reflect specific details that may be relevant to the overall assessment results.
3. Repeating the process for population subgroups, most often women and girls, older persons (over 64 years), children under 5 years and people with a physical disability.
4. Assigning confidence levels to each assessment. This can be done at the time of an individual assessment (preferred) or after a round of assessments for an SDS type.
5. Repeating the process for each SDS type relevant for the area being assessed.

This section describes a process for using expert understanding of SDS vulnerability, together with data collected on SDS types and frequencies, to develop a comparable understanding of SDS risk. The process uses **Table 4. Scaling vulnerability to sand and dust storms**.

Step one – Define why the assessment is needed

A clear purpose and justification for assessing SDS risk should be developed, preferably linked to SDS risk reduction.

Step two – Define the location for the assessment

A well-defined assessment area should be selected to reduce confusion over the applicability of results and facilitate the collection of background data and planning.

Step three – Design the assessment workshop

An expert-based assessment will normally take place in a workshop format, generally for one day. The design of the workshop should involve:

- Identifying between 7 and 12 experts who will participate (the number depends on their experience). They should be experts in one of the areas related to SDS or knowledgeable about the population in the assessment area. These experts can include meteorologists, geographers, sociologists, agriculturalists, community development experts, experts on gender, age and disability, health officials (doctors as well as public health specialists), engineers responsible for infrastructure at risk from SDS and government officials involved in disaster risk management.
- Identifying a location for the workshop that provides sufficient meeting space and facilities for a one-day workshop.
- Selecting one or more workshop moderators experienced in the methods used to develop consensus when dealing with diverse information and potential ambiguity. Although the moderators do not need to be knowledgeable about SDS before a workshop, they should be fully cognisant of the workshop briefing materials before the workshop. Where moderators knowledgeable on SDS are available, they should be used.
- Identifying any specific information or materials (for example maps) that should be assembled before the workshop.

- Developing an assessment workshop agenda covering the purpose of the workshop, methods, ground rules and expected results (see **Step six**)
- Defining how the workshop results will be disseminated and validated.

Step four – Collect background data

Background data should include physical, demographic (for example gender, age, disabilities), economic, social and other information that describes the population to be assessed. Specific details (for example frequency, intensity, duration) of past SDS events should be collected and compiled into a narrative summary based on the typology set out in **chapter 3** and **Table 2**. **Sand and dust storm hazard typology**.

Step five – Sharing information before the workshop

An information package should be shared with workshop participants before the event. The package should include (1) The background and reason for the workshop, (2) Information on SDS in the assessment area (for example SDS types and return times) and other background information collected in Step four, (3) Logistics arrangements, (4) Ground rules and (5) A reasonably detailed description of the process to be used in the workshop.

In general, most participants will not (or at least not fully) read the information package but any improvement in knowledge about the workshop process or SDS gained before the workshop will help the workshop process operate with fewer problems.

Step six – Conduct the workshop

The workshop should be led by one or more moderators and generally follow these agenda points:

- opening, introductions and objectives of the workshop
- background to SDS in the assessment area, including handing out of SDS typology and return period information
- review of background information on the assessment area, including handing out of background information
- review of the assessment process (see **Box 10. Expert-based assessment process overview)**
- conduct the assessment process in as many rounds as needed to cover the SDS types identified for the assessment area
- summarize results
- describe how the results will be used
- conduct a short workshop assessment covering the workshop process and facilities and services
- closing

As appropriate, there can be opening and closing speeches as well as certificates provided indicating that participants assisted in conducting the SDS assessment.

Step seven – Document, disseminate and validate results

As per Tasks 8 and 9 of the **Framework (Table 5)**, workshop results should be compiled into a report and validated by sharing with those affected by SDS and living in the assessment area. A level of confidence in the survey results should be included in the final report. See **chapter 5.7** on setting confidence levels.

An expert-group assessment report can report results for specific vulnerabilities to specific types of SDS. An example of such reporting out is provided in **Box 11. Sample simple expert assessment results report-out – SDS risk**.

A second approach is to calculate a number that indicates the relative importance (size) of the overall vulnerability assessment and to present it in a spider diagram for each group covered by the assessment, and for each SDS type. This is done by calculating the area of each triangle that makes up the spider for each group/type combination covered by an assessment.

The resulting number indicates the relative importance (size) of each of the six vulnerability factors (capitals) when compared to a scoring of "extreme" (vulnerability) and "insignificant" (vulnerability) for all six factors considered.

The resulting numbers can be used to compare vulnerability across locations and across groups. They can also be used, in an X/Y plot, to indicate comparative levels of risk, as described above.

The use of the area calculation avoids, in large measure, the issues related to attempting to compare very different characteristics of vulnerability in the absence of a standard metric for all characteristics, such as economic value or a research-based way of comparing different types of vulnerability. Procedures for calculating spider diagram area and further discussion on this approach can be found in CAMP Alatoo and UNDP Central Asia Climate Risk Management Program (2013). The calculation process can be set as a formula in Excel® or similar software, so that the results are generated automatically once vulnerability scores have been entered.

Normal (academic) good practice should be used in writing the assessment report. The procedures used should be clearly described and the results understandable so that the same process can be used elsewhere and results can be compared.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Box 11. Sample simple expert assessment results report-out – SDS risk

An expert assessment of SDS impacts on people living in Zira District was conducted by a team of experts from the fields of meteorology, geography, social sciences, agriculture, community development, health and engineering. Zira District has a population of 5,632 (52 per cent female), with a median per capita income of US$ 3,760. The main occupation is semi-mechanized farming (wheat, maize) and the poverty rate is 15 per cent.

Based on weather data from Zira airport, Type One storms have a return period of twice a year, Type Two events twice a year, Type Five events three times a year and Type Six events once a year. Type Three and Four events were not reported based on airport data.

The assessment covered the general population, women and girls and older persons. The results presented in the following graph for Type Five SDS (high intensity-very small area) indicate that this SDS has:

- a large impact on the health of older persons, with effects (albeit less severe) on women and girls and the general population
- a large impact on financial capital for women and girls, possibly due to increased costs of cleaning following SDS
- a medium impact on the financial capital of older persons, likely due to the need for medical care

EFFECTS OF TYPE FIVE SDS ON ZIRA POPULATION AND SUBGROUPS

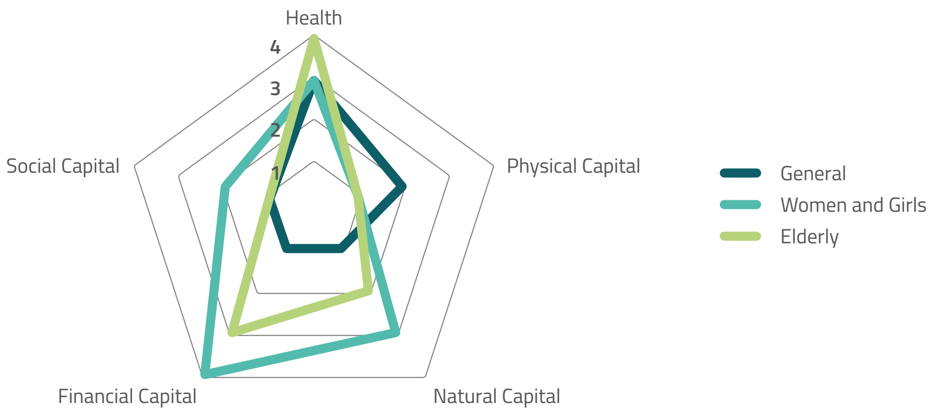

Figure 16. Effects of type five SDS on Zira population and subgroups

Note: Vulnerability effects scores where Extreme = 5; High = 4, Medium = 3, Low = 2 and Insignificant = 1.

5.7 Assigning confidence to results

There is a need to indicate the level of confidence in assessment results. The challenge is that the information used to generate results may not be uniform for all locations covered, for all relevant data sets used, or for the same data sets used in different assessments.

Clearly stating the level of confidence that assessors have in the results of their work is professionally appropriate. It also allows those using the assessment results to factor any limitations into their decision-making process.

For a questionnaire-based assessment, the statement of confidence can be developed based on the results of statistical analysis and reference to operational challenges faced in conducting a survey. These challenges will typically include no access to some of the assessment areas, large numbers of refusals to participate, confusion as to the types of SDS discussed, unwillingness to answer specific questions and difficulty in ensuring gender-balanced surveys.

For the expert-based process, one option for assessing confidence is through external reviews. This is good practice but, in the case of SDS assessments, presents three challenges. First, there may not be sufficient experts not involved in a specific assessment to conduct a robust external review, or there may be an insufficient number of experts to review numerous local or regional scale assessments.

Second, the external reviewers may disagree between themselves, and with the initial assessors, on the substance and rigour of the data used, leading to disagreements about the data even before they review the results.

Finally, there may not be agreed metrics by which to define substance and rigour for individual pieces of or groups of data, which makes understanding these parameters – as part of the initial assessment and as part of the review process – a challenge.

Another option, used in the **Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation** report (Intergovernmental Panel on Climate Change, 2012), is to establish a set of terms that define the assessors' confidence in the (1) quality of the data used, and (2) the accuracy of the results.

Adapting this approach to SDS assessments, the quality of data used can be rated as having:

- poor representation of the spatial or temporal scope of the assessment
- fair representation of the spatial or temporal scope of the assessment, or
- good representation of the spatial or temporal scope of the assessment

In each case, the definition of spatial or temporal scope would depend on the scale of the assessment. A data set may be spatially and temporally good for a specific location when assessing a specific type of SDS, but spatially and temporally poor when used as part of a continent-level assessment for all types of SDS.

Confidence in the assessment results can be assessed as being:

Low, where

- a considerable part of the data needed for the assessment is not available or
- the data used may have a weak connection to the issue of concern or
- the actual understanding of the physical or social processes involved is weak.

Medium, where

- the required data are generally available and
- there is a reasonable connection with the issue of concern and
- there is a basic understanding of the physical or social processes involved.

High, where

- all the necessary data to conduct a robust assessment are available and
- there are clear linkages between the data and the issue of concern and
- the physical and social processes involved are well understood.

To avoid overstating confidence, an assessment is rated by the lowest descriptor. For instance, where data are available but weakly connected to the issue of concern, the rating would be "low confidence".

Where the assessment of the impact on one type of capital is considered to have greater or less quality or confidence than for other information used, this should be stated as part of the overall statement of confidence. The more specific statements of confidence and data quality are for data sets under the assessment, the more transparent and credible the assessment results.

Ideally, confidence in results should be stated for each segment of the assessment process, for instance, for health and the general population; for health and women and girls; and for health and older persons. If this cannot be done, the experts involved in the assessment should set overall confidence levels for each of the major sources of vulnerability covered. In addition, confidence in the SDS typologies used should also be indicated.

All confidence statements should be consensus-based. If there is an inability to agree on specific confidence levels, then a majority and minority statement can be made, accompanied by short justifications.

5.8 Using risk assessment results

(This section should be read in conjunction with **chapters 3, 5.5, 5.6, 9, 10, 12** and **13**). The purpose of a risk assessment is to identify risks so that they can be reduced. For disaster risk reduction to be effective and efficient, the most salient risks need to be prioritized for mitigation or reduction to acceptable levels.

Both assessment methods provide results that identify risk salience and can guide risk reduction interventions. The potential uses of SDS risk assessment results for risk reduction can be summarized as follows:

- **SDS risk management policy:** Results from either assessment process can frame SDS risk reduction policy by providing evidence-based identification of the importance of risks from SDS. As the expert process can be quicker and cover larger areas than the survey process, its use in policy development (for instance a national SDS risk management strategy) can be more direct.

The survey process provides stronger evidence-based results (due to the use of statistical analysis), but can take more time and be more costly. At the policy level, these results can be used to refine strategies for more specific interventions addressing the range of risks identified as salient for the at-risk population.

- **SDS warning:** Warning of SDS events is based on research into the hazards and the identification and monitoring of triggers. The survey process can help identify which triggers are most relevant to at-risk populations (as people respond best to warnings based on triggers they know and understand), and their receptivity to specific actions that can be taken to reduce SDS impacts, depending on the type of SDS event for which warnings are provided.

- **SDS response:** In general, specific disaster relief and recovery operations are not undertaken for most SDS. The expert process can help identify and raise the profile of SDS response options by identifying where specific responses can be most effective in reducing SDS impact. An example would be linking SDS health vulnerability and risk to specific subpopulations and identifying the effectiveness of response efforts for this subpopulation. Survey-based results can also identify local SDS coping or adaptation measures that can be formalized into SDS response plans. This input is very useful in ensuring that response measures match local capacities and preferences.

- **Risk reduction:** Both assessment procedures can identify where risk reduction efforts should be targeted, with the expert process more focused on strategic interventions and the survey process more focused on on-the-ground interventions. Both procedures can be used to assess the costs-to-benefit decision points for specific SDS risk reduction interventions or for packages of interventions.

  The survey process can be used to identify the salience of specific SDS impacts for at-risk groups, which can then be used to define preferences for specific risk reduction options. As noted, survey results are likely more useful than the expert process in planning specific SDS risk reduction interventions. Initial surveys can be used to define baselines and subsequent surveys (often using reduced sampling) can be used to assess progress in reducing perceived SDS impacts and levels of risk.

  These uses of assessment results to address SDS risks need to be matched by a good understanding of the physical processes and impacts related to different types of SDS in different locations. Results from both assessments can be used, in part, to guide where research into local SDS causes and impacts should be targeted, by type of impact, location or at-risk group.

  Finally, results from both assessments of risks from specific hazards can feed into larger assessments and strategies related to the management of other hazards and risks, such as from flooding, severe weather, or drought. In this sense, SDS risk assessments further the integration of SDS into mainstream disaster risk management.

5.9 SDS survey questionnaire

5.9.1. Details of the model questionnaire

Table 6 provides a model for the field-level SDS risk assessment questionnaire which is presented in table format to include instructions and guidance. This information should be removed from the actual questionnaire but can be provided to the teams conducting surveys to assist their work. To ensure that results are comparable across surveys and assessments, the scaling of the response to questions should not be changed.

The questionnaire is designed to be administered to one person, but questions and responses are based on the assumption that it will take place in a household. The questionnaire wording should be modified if it is clearly only being administered to a single person or is being carried out with a focus group or through a key informant interview (The latter is not preferred as the scope of coverage would be limited).

Use of the questionnaire should follow normal good practice for data collection. Anyone with whom the questionnaire is used should be provided with an explanation of the purpose of the survey, how the results will be used, and particulars of the survey process and organizations involved.

5.9.2. Sample size

Questionnaire-based surveys have no defined limit regarding the maximum number of people, households or other groups that can be included in the survey. The maximum target population is generally defined through a combination of time to conduct the survey, funding and staffing. Setting the statistical confidence level and indicator for a survey can determine practical maximum and minimum limits for the sample size.[4]

5.9.3. Modifications to the questionnaire

The model questionnaire should be revised to reflect local conditions and the focus of the survey work. Additional questions can be added to the survey form, for instance to include perceptions of other hazards besides SDS. However, a field-tested survey should not take more than 30 minutes to administer, including introductions, completing the form and any other formalities.

If the survey is carried out on a one-to-one basis, gender and age information is already collected in the form. Using this information to disaggregate responses would be a normal part of the analysis and report-out process.

If the questionnaire is used to collect household responses (i.e. not one-to-one with an individual), the number of questions needs to be increased to allow for information to be collected on effects that may be different for males and females (generally men and women but also, where appropriate, boys and girls). This can be done for each of the "effect" question sets (items 27 to 41), by adding additional questions following the format of *Are these effects the same for men and women or boys and girls? If not, is there 1 - no effect, 2 – very limited effect, 3 – some effect, 4 – important effect, 5 – very severe effect*, and recording the answers separately for each group covered.

The different responses, if any, are then used in the analysis and report-out of the survey to differentiate SDS impacts by the groups covered.

Item 25 of the model questionnaire provides for collecting a statement from the person or group being interviewed describing the characteristics of an SDS event, and then estimating the reduction in visibility to match the description as closely as possible to one of the SDS types described in **Table 2**. This process could be time-consuming and the respondent may have difficulty in accurately and quickly determining visibility distance.

The alternative is to prepare pictures of each type of SDS in advance with descriptive text covering the key points from **Table 2**. These pictures would be shown to the respondents, who would choose one or more pictures as the basis for covering items 25 to 40 in the questionnaire. This use of a visual reference makes it clearer to the respondent what the survey questions are about and makes the classification of the response by SDS type clearer and more credible.

5.9.4. Information on SDS risk management

The model survey in **Table 6** is focused on collecting information on SDS impacts. Additional questions can be added to collect information on SDS preparedness, response plans, warning systems, information dissemination and ongoing mitigation activities.

The challenge with adding questions is that they can make the survey overly long, thereby reducing the number of surveys that a team can complete in a designated time, and taking excessive time from those who are being questioned. Testing of the questionnaire can assess whether its length is excessive or whether questions on SDS risk management are appropriate.

4 Confidence level and confidence indicators can be calculated at https://surveysystem.com/sscalc.htm or similar sites. (Reference to a commercial website does not indicate a recommendation or support for the company involved.)

An alternative is to use key informants to explore how SDS risks are managed, particularly as statistics on risk management options are not needed. Key informants include officials, individuals, households, businesses and academics.

A strategy of diversifying sources of information can assist with developing a broad understanding of SDS risk management practices.

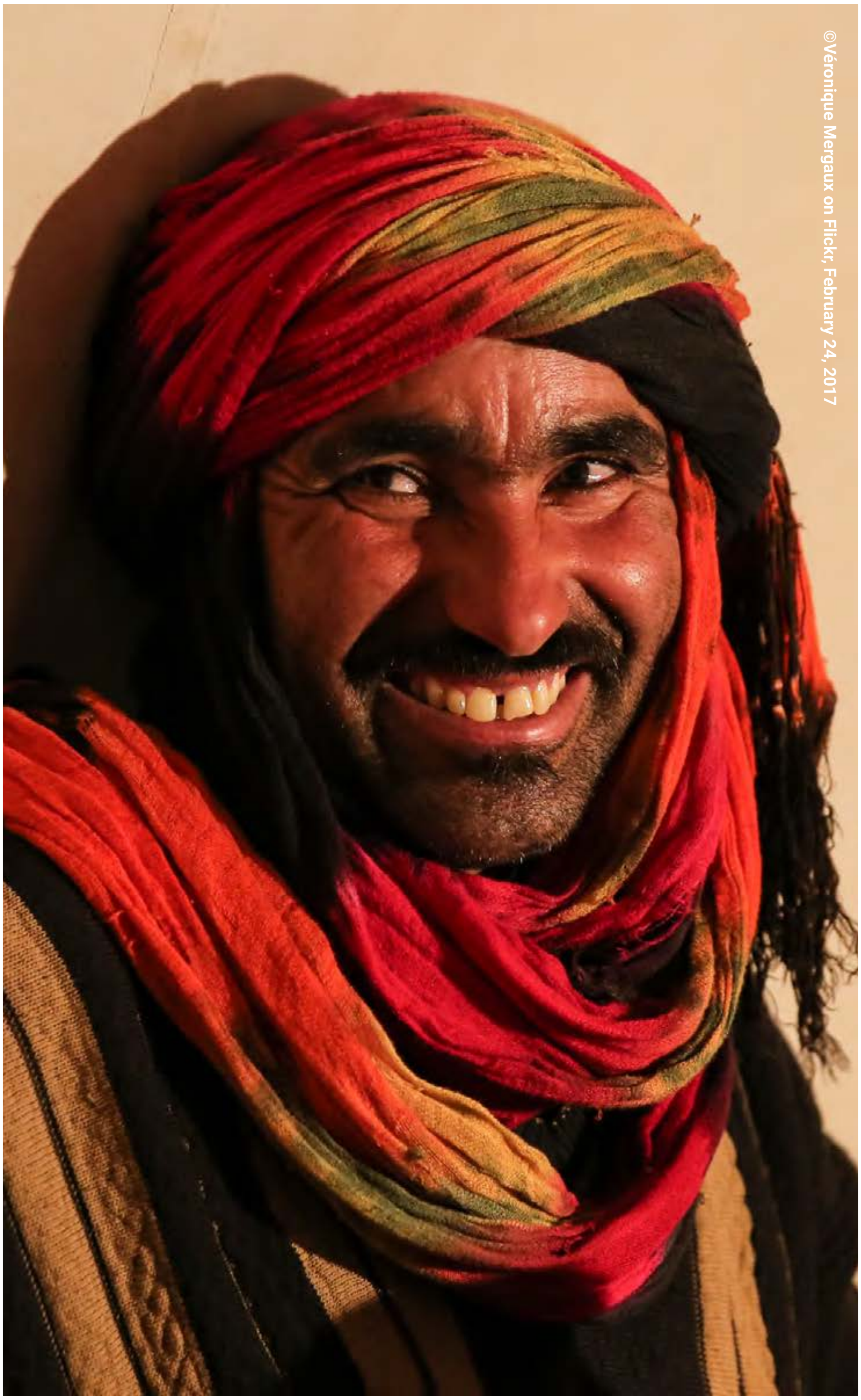

Table 6. Sand and dust storm perception survey

Sequence number	Information/question	Information to be entered	Notes
1	Date		
2	Surveyor 1	Name	One surveyor should be male and one female.
3	Surveyor 2	Name	
4	Sequence number	Number indicating the sequence of the survey, starting from 1	The sequence number can include a letter or additional number indicating the team that conducted the survey.
5	Location	Town or other location where the survey is taking place	
6	GPS reference	Global Positioning System reference for the place of the interview	
7	Gender of the respondent	Male or female	
8	Agreement to conduct survey	Yes or no	The person surveyed should agree to the survey. If not, the survey is ended.
9	Age	In years	Age can also be collected using a range of ages, for example 10 to 19, 20 to 29, etc.
10	Is the respondent the head of the household?	Yes or no	
11	If the respondent is not the head of the household, what is the gender of the head of the household?	Male or female	
12	What is the profession of the head of the household?	Select from list.	A list of typical professions should be added before the questionnaire is used.
13	How many persons are resident in the household at the time of the survey?	Number	The number should not include persons who are not currently sleeping in the household (i.e. people who are traveling or working somewhere else temporarily).
14	Of these persons, how many are female?	Number	
15	Of these persons, how many are under five years of age?	Number	
16	Of these persons, how many are over 64 years of age and what is their gender?	Number and gender	
17	Are there any persons with disabilities resident in the household and what is their gender?	Yes or no, with gender indicated	
18	If yes, list the types of disabilities.	Select from list.	Prepare the list in advance.
19	Does the household rent or own the place where they live?	Renters or owners	

Sequence number	Information/question	Information to be entered	Notes
20	Does the household have electricity?	Yes or no	
21	Does the household have running water?	Yes or no	
22	What type of sanitation facility does the household use?	Select from list.	Prepare list in advance.
23	Does the household own any of the following: car, TV, radio, computer, tractor or truck, boat?	Yes or no for each item	Update the list based on likely local ownership of assets.
24	Has the household experienced a sand or dust storm?	Yes or no	If no, end the survey.
25	If yes, ask for a description of the most recent event. Prompt for: when the SDS occurred (month, year) time of day how long it lasted how much visibility was reduced at the worst point in the storm. Use a reference point, for instance a tree or building that was not visible during the storm.	Write down the response.	After the question, estimate the distance to the structure or reference point not visible during the storm.
26	With reference to the storm described, ask how frequently per year these events take place.	Indicate per year	If less than once a year, indicate how often over a number of years, for instance, once in five years.
27	Ask whether the storm described had an effect on the health of anyone in the household.	Answer scale: 1 – no effect 2 – very limited effect 3 – some effect 4 – important effect 5 – very severe effect	
28	For answers 2 to 5 on the scale, ask for a description of what happened.	Write down the response.	Detail for each affected individual. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
29	Ask whether the storm described had any effect on buildings, roads or other infrastructure (water systems, irrigation, electrical systems, communications) where the household is located.	Answer scale: 1 – no effect 2 – very limited effect 3 – some effect 4 – important effect 5 – very severe effect	
30	For answers 2 to 5 on the scale, ask for a description of what happened.	Write down the response.	Include as much detail as possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.

Sequence number	Information/question	Information to be entered	Notes
31	Ask whether the storm described had any effect on the household's fields, crops or garden production.	Answer scale: 1 – no effect 2 – very limited effect 3 – some effect 4 – important effect 5 – very severe effect	
32	For answers 2 to 5 on the scale, ask for a description of what happened.	Write down the response.	Include as much detail as possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
33	Ask whether the storm caused soil loss or other erosion.	Answer scale: 1 – no effect 2 – very limited effect 3 – some effect 4 – important effect 5 – very severe effect	This question focuses on the impact of a location contributing sand or dust to an SDS event through wind erosion.
34	For answers 2 to 5 on the scale, ask for a description of what happened.	Write down the response.	Include as much detail as possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
35	Ask whether the storm caused the household to lose income (i.e. someone could not work or their business could not function due to the storm).	Answer scale: 1 – no effect 2 – very limited effect 3 – some effect 4 – important effect 5 – very severe effect	
36	For answers 2 to 5 on the scale, ask for a description of what happened.	Write down the response.	Include as much detail as possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
37	Ask whether the storm described had any effect on land, pasture, forests or other natural resources that are available to the household.	Answer scale: 1 – no effect 2 – very limited effect 3 – some effect 4 – important effect 5 – very severe effect	
38	For answers 2 to 5 on the scale, ask for a description of what happened.	Write down the response.	Include as much detail as possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
39	Ask whether the storm described led the household to use their social connections to deal with the effects of the storm.	Answer scale: 1 – no 2 – very limited use 3 – some use 4 – important use 5 – very significant use	Note that "social connections" can be reworded to reflect kinship ties, extended family or other social connections that are common in the location where the survey is taking place.

Sequence number	Information/question	Information to be entered	Notes
40	For answers 2 to 5 on the scale, ask for a description of which connections were used and for which purposes.	Write down the response.	Include as much detail as possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
41	Ask whether the effects of the storm had, in their opinion, been reduced by warnings or any other actions taken by the Government.	Answer scale: 5 – no 4 – very limited reduction 3 – some reduction 2 – important reduction 1 – very significant reduction	Note that the answer scale is the inverse for the other responses, making "very significant reduction" the opposite of "very severe effect".
42	For all answers, ask for a description of the actions taken.	Write down the response.	Include as much detail as possible. The impacts of warnings should be linked to one or more of the capitals if possible. Note gender, age and disability status (if appropriate) for each respondent or person discussed.
43	Ask the household whether they have experienced any other types of sand and dust storms in the past.	Yes or no	
44	If yes, repeat items 25 to 41 for this event.		After the second round with items 25 to 41, ask again if there are any other sand or dust storms that the household remembers. If yes, repeat the process until all storms mentioned by the household are covered per items 25 to 41.
45	If no other storms are reported, ask the household to rate the significance of the storms they described against the effects of floods.	Rating 1. Not significant 2. Much less significant 3. As significant 4. More significant 5. Much more significant	This item and the next should include the most significant natural hazards identified for the assessment area. Note gender, age and disability status (if appropriate) for each respondent or person discussed. Seek input from men, women, girls and boys.

Sequence number	Information/question	Information to be entered	Notes
46	If no other storms are reported, ask the household to rate the significance of the storms they described against the effects of drought.	Rating 1. Not significant 2. Much less significant 3. As significant 4. More significant 5. Much more significant	Additional items can be added to cover additional hazards. Note gender, age and disability status (if appropriate) for each respondent or person discussed. Seek input from men, women, girls and boys.
47	Close by thanking the respondent and telling them when a report based on the survey will be available.		

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5.10 Conclusions

This chapter has covered practical ways of assessing the risks posed by SDS to at-risk populations. Two approaches have been defined based on (1) expectations of data reliability and spatial consistency across all SDS-affected locations and (2) a need to deliver practical results that can help reduce SDS impacts.

One assessment approach uses questionnaire-based surveys of populations at risk of SDS to combine perceptions of SDS vulnerability with a typology of SDS events and generate results that are comparable across locations and scales. The second assessment approach uses expert knowledge and the SDS typology to define vulnerability levels and risks, which are also comparable across scales.

Either approach can be used at very local, national or regional scales. If either approach is used consistently between locations, the results from each approach can be compared and, when appropriate, aggregated to increase understanding of SDS impacts and risks.

The survey approach can be used to cover a wide geographic area and uses random or selective sampling to collect information on a wide range of affected populations. These results can then be shared as part of the expert approach to aid experts in developing a common understanding of the SDS hazard and impacts and in framing the decision-making process. This process uses the strengths of a perception-based understanding of SDS risk and the strengths of an expert understanding of the physical, economic and social consequences of SDS.

The cost of the survey process depends on the scale of the survey: the larger the at-risk population covered, the greater the expected cost for an individual survey. Surveys are likely best done at subnational scales defined by SDS source and impact locations and then aggregated to national and subglobal results. The survey approach can be implemented by commercial survey firms, non-governmental organizations, civil society groups, academic institutions or government statistical offices and can be part of larger assessments of hazards or socioeconomic or health conditions.

The cost of the expert process is considered relatively low per workshop. Each assessment workshop can cover the subnational to national level in scale, again defined by the types of SDS of concern. These workshops can be organized by governments, academic institutions or international organizations.

The two approaches set out are based on current practice for assessing disaster risk, hazards and vulnerabilities, but have not been tested or validated in the field. Validation may yield changes to both approaches and the underlying procedures and supporting materials. Where these changes are necessary, they should be applied consistently within each approach to ensure that assessment results are comparable.

To date SDS, as hazards and potential disasters, have not gained significant attention within the disaster risk management community. Providing practical assessment procedures will enable this community to better understand the threat posed by SDS and to develop effective measures to reduce these risks.

5.11 References

CAMP Alatoo and United Nations Development Programme (UNDP) Central Asia Climate Risk Management Program (2013). *Climate Risk Assessment Guide – Central Asia*.

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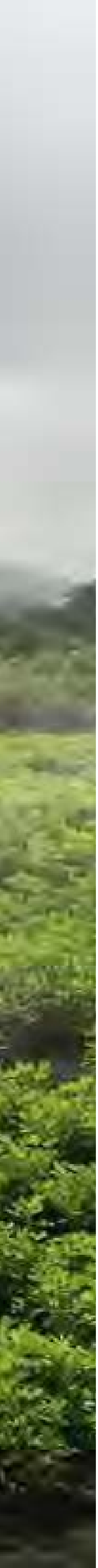

6. Economic impact assessment frame-work for sand and dust storms

Chapter overview

This chapter discusses different approaches to assessing the economic impact of sand and dust storms (SDS). The chapter begins with a review of research into SDS, followed by an extensive discussion of the different types of costs which need to be considered when assessing the economic impacts of SDS. This is followed by a review of the different methods which can be used to assess economic impacts and an extensive discussion of the cost-benefit (or benefit-cost) method as applied to SDS. The chapter concludes with a review of the data sources which should be used in the cost-benefit method and in the overall assessment of the economic impact of SDS.

6.1 Damage, costs and benefits of SDS

6.1.1. Reviewing the costs and benefits of SDS

Sand and dust storms (SDS) differ from many other disasters in that there is usually very little major structural damage. The physical damage caused by SDS is relatively minor when compared to other disasters such as earthquakes or floods.

SDS do not usually result in directly attributable fatalities or injuries, with most health-related impacts associated with other health conditions such as respiratory diseases, eye problems or cardiovascular diseases. However, SDS can be the proximate cause of fatalities and injuries due to transport accidents, most commonly road accidents in conditions of high sand and dust.

The most evident damage caused by SDS is impacts on the natural environment due to, for instance, dust and sand accumulation or inundation on croplands. Sand and dust can also affect infrastructure operations by entering commercial, manufacturing or residential structures, leading to productivity- or production-related issues, as well as the need for cleanups, removals or limiting economic activity. Neither the human nor the financial impacts of SDS are well captured in international disaster databases, such as those maintained by the Centre for Research on the Epidemiology of Disasters (see **chapter 3**).

The economic impact of SDS is somewhat unique, in that there is a cost at the source of the sand or dust emission through losses in soil and/or sand and associated losses in productivity or income. In areas where there is no direct economic activity, indirect costs will still be incurred through loss of soil nutrients or carbon, and perhaps ecosystem services. There are also costs imposed on the region downwind of the emission region, due to economic disruption caused by the event(s), such as closure of transportation services and cleaning of roads, houses and business premises (Huszar and Piper, 1986; Tozer and Leys, 2013).

The impact of SDS can be mitigated at the source with investments in soil and land management practices, such as using forestry or cover crops to reduce soil losses or movement of sand when weather conditions could lead to an SDS event. Furthermore, the effect on the downwind region can be reduced with mitigation practices such as installation of air filtration systems or early warning systems to ensure that members of high risk populations remain indoors.

However, the net benefits and/or costs of mitigation, either at the source or in the impact region, need to be considered in the context of the overall cost of SDS to an economy. This consideration needs to take place either in a region within a country (such as a province, state or set of states), country or global region (including several countries), such that the benefits of mitigation outweigh the costs.

Measuring the impact of SDS for each country is critical as it allows the government of a country to determine if the costs of SDS can be moderated through an investment in mitigation projects within the country in the source area. The key aspect here is that the benefits of dust mitigation outweigh the costs of the mitigation measures, recognizing that the control of all SDS impacts may be not feasible from a financial perspective.

It is important to recognize that most benefits of mitigation will accrue to individuals, but most of the costs are incurred by the government or government agencies. Thus, even though there may be a net benefit, the funding agency may not have sufficient funds to finance the mitigation programme. What must also be remembered here is that the objective is to reduce the effects of dust on the population in the impact region, not to eradicate SDS completely, as SDS are part of the natural cycles of the world and therefore total removal of SDS is undesirable from a total environmental perspective.

Dust mitigation projects may also be undertaken in source regions outside the national boundaries of a country, as airborne dust particles have been shown to travel long distances, hence there can be a significant distance between the source region and the impact region. As a result, the benefits and costs of a mitigation programme may fall on, or be incurred by, different countries or regional government instrumentalities. However, the major decision criterion is that the net benefits of the programme (the sum of benefits in both the impact and source regions) exceed the costs.

There are numerous approaches to measure the economic impact of SDS and to measure the costs and benefits of mitigation programmes. To that end, this chapter presents a method of measuring the costs of SDS on the impact region and provides a framework to measure the costs and benefits of various mitigation strategies in either the source or the impact regions.

6.1.2. Previous economic impact studies

Given the prevalence of SDS around the world, the number of economic impact assessments is very limited. In one of the first attempts at measuring the economic impact of SDS, Huszar and Piper (1986) used surveys of businesses and households to quantify the off-site costs of sand and dust storms in New Mexico, in the United States of America (USA). Huszar and Piper (1986) estimated the costs of SDS in New Mexico alone were approximately $857 million (in 1985 dollars). This is only the cost to households and businesses and does not include other costs such as the removal of sand and dust from roads by city, county and state transportation authorities, nor does it include defence force costs for cleaning airbases located in the state.

In a study of the costs of wind erosion, or SDS, in South Australia, Williams and Young (1999) estimated the annual average costs of SDS events to the population of that state was $A 23 million (in 1999 Australian dollars). Most of the cost ($A 20 million) was health related. The range of costs estimated by Williams and Young (1999) was from $A11 to $A56 million.

Ai and Polenske (2008) used Input-Output (I-O) modelling to estimate the costs of SDS in Beijing in 2000. The authors concluded that the delayed impacts of SDS exceeded the immediate effects. Delayed impacts are those that do not occur on the day(s) of a dust event but are consequences of the dust storm. Immediate effects occurred in the construction, trade and household sectors, and totalled $US 66 million. Delayed effects on the agricultural and manufacturing sectors totalled US $198 million. Together, the total economic cost of SDS was $US264 million (in 2003 dollars).

Miri et al. (2009) estimated that SDS cost the Sistan region of eastern Iran US$ 125 million from 2000 to 2004. Most of the costs – 61 per cent – were reportedly related to household cleaning and reduced electronic equipment life. A further 25 per cent were associated with the cost of health-related issues, including hospital admissions.

Measuring the economic impact of one significant dust storm in New South Wales, Australia, Tozer and Leys (2013) estimated the costs to be $A299 million (range of $A293 to $A313 million in 2012 Australian dollars) in that state alone, without measuring the impacts on other states which experienced the dust storm. Most of the impact was on the household sector, with 85 per cent of the costs. The next two most impacted sectors were transport (principally air traffic) and commercial activity.

SDS economic impact was studied in Kuwait, with the impact on the oil and gas operations estimated to cost $US 9.36 million in 2018 (Al-Hemoud et al., 2019). Also, oil export losses due to closeout of marine terminals were estimated at US $1.03 million per ship (Al-Hemoud et al., 2017). Airline delays due to airport operations shutdown were also estimated.

6.2 Types of costs in the context of SDS

6.2.1. Direct and indirect costs

Several researchers define two types of costs associated with disasters – direct and indirect (see, for example, Hallegatte and Pyzyluski, 2010). Direct costs are those associated with the immediate impact of a disaster. In the context of SDS, most costs are direct costs, as the impacts of SDS do not typically have long-term effects on an economy in the same way as damage and reconstruction caused by hurricanes and earthquakes does, requiring rebuilding of damaged structures and functions within the economy of the affected area.

Indirect costs are those that are imposed on an economy due to business disruptions or other similar impacts brought on by a disaster. As noted, SDS do not have a long-term impact on most of the economy. A thorough review of the economic impact studies related to SDS events is presented in Al-Hemoud et al. (2019).

One set of indirect costs that SDS may impose on an economy is due to the long-term loss of income for landowners in the SDS source region(s). Depending on the level of loss, indirect costs may exceed direct costs in some regions. From a socioeconomic perspective, this can have long-term impacts, particularly if the costs push a vulnerable population past a critical threshold.

6.2.2. Market and non-market costs

Market costs are those costs that can be directly estimated due to a market for a product or that can be estimated using a market valuation technique. In the context of SDS, many of the damage costs can be estimated using market cost, in that there are established markets for the products or services affected.

Non-market costs or values are for damage or products for which there is no direct market. Examples of products or damages that fit into this category include damage to cultural icons or historic sites, environmental or ecosystem services, or human lives.

There are some ways to measure the economic impact of events on human life, such as disability-adjusted life years (DALY) or quality-adjusted life years (QALY) (World Health Organization [WHO], 2016). However, these are used as an index for the value of all lives and do not take into account many social, cultural and economic factors (Arnesen and Nord, 1999). There are also accepted methods to estimate non-market values for environmental services or loss in revenue from cultural or tourism events, such as contingent valuation (willingness to pay) or travel costs (Hanley and Spash, 1993; Harris, 2006; Ninan, 2014).

6.2.3. Cost and value

One important distinction to make is the difference between cost and value. A 'cost' is how much a person has to pay for a product, or the price of that product, which is usually reasonably easy to observe in a marketplace. In contrast, 'value' is somewhat subjective, and is a measure of what a person would be willing to pay for a product or service that may not have a fully functioning market.

> The key difference here is what a person has to pay against what they are willing to pay. In the context of SDS, much of what is discussed in the following sections will be a cost-based analysis. However, when discussing effects of SDS, such as damage to cultural icons or reduction in ecosystem services, methods of assigning value to these types of services will also be discussed.

6.2.4. On-site (source) and off-site (impact)

SDS create damage in two locations, the source location and impact region. The economic impact in either location will depend on many things, such as the level and types of economic activity in either region, the activities undertaken in the source region that may contribute to SDS events, such as farming or cropping, the relative wealth of the population in each location and damage to the environment or ecosystems in either location. Other factors that need to be considered include damage to environmental or ecosystem services in either region, or the human aspects, such as health and income distribution in the source and/or impact region.

6.3 Gender, age, disability and economic analysis

Gender, age and disabilities are important to consider in assessing the economic cost of SDS. Specific impacts may be greater for men, women, boys or girls due to their social or economic situations. For instance, if men are obliged to work outside in areas where SDS are common, then impacts on their health could be significant and could have an impact on how long or how often then can work.

Similarly, age and disability are factors in some of the health impacts of SDS. For instance, older persons are potentially more vulnerable to respiratory or cardiovascular conditions which can be exacerbated by SDS. These SDS impacts may increase health care costs, require other family members or hired help to assist the affected or take affected persons away from productive activities.

To the extent that disaggregated data are available, economic assessment results should identify the extent to which SDS impacts affect different gender, age and disability groups in terms of participation in, and benefiting from, the economy. This type of analysis can be useful in tying statistical analyses used in economic impact assessments to real challenges faced by SDS-affected groups.

6.4 Economic impacts of SDS

6.4.1. Impacts to consider

Research on the economic impact of SDS has focused on the direct impacts on the main drivers of an economy, such as transport, manufacturing or the costs of cleaning incurred by households and industry (Huszar and Piper, 1986; Tozer and Leys, 2013).

However, two other major components in a society can be significantly affected by SDS in either the source or the impact region. These are (i) the environment or ecosystem within a region or country and (ii) the human dimension, beyond losses of income due to lower production or sales. However, the key concept here is that the three components; economic, environmental and human, are all tightly interlinked, meaning that they cannot be easily separated when measuring the overall economic impact of SDS.

The impacts of SDS on the economic activity within a source or impact country or region are relatively easily measured and in most cases are direct costs, with some minor indirect costs. Environmental or ecosystems services can be severely affected by SDS in either the source or the impact region, depending on the environment or ecosystems in each region.

In the source region, soil erosion, damage to waterways and/or habitat or ecosystem loss or damage are some of the consequences of SDS emissions. Air quality, waterways siltation and ecosystem damage are some of the environmental consequences in the impact region of SDS.

The human side of the impacts of SDS are a little more complex to disentangle due to differences across regions or countries from which SDS are sourced and/or impacted. The reasons for this are due to (i) the complexity of economic welfare and equality in the source and/or impact regions and (ii) how erosion of the soil – the source of material for SDS – affects the livelihoods of those relying on it as a source of food and/or income.

Another reason for this complexity is that soil erosion is a dynamic factor affecting production and productivity of land in the source region. Incomes are not only affected in one year by soil erosion. If erosion continues, then production – and, by extension, incomes or wealth of the population in the source area – will be continually reduced until the soil is unable to sustain any cropping activities at all, hence reducing food supply or landowner income on the affected land to zero.

Another aspect of the human side of the impact of SDS is the health of the population, at the source or, more commonly, in the impact region, in that dust has been shown to negatively affect certain segments of the population. This is a somewhat complex situation. An SDS event may trigger a health crisis leading to a fatality, but attributing this fatality to SDS may be difficult, for several reasons. The person may have had a history of health problems before the SDS event, such as cardio-pulmonary issues. This places them in a high-risk category. There may have been a significant timespan between the SDS event and the health effect.

Similar issues exist in the case of non-fatal health events, such as an acute case of difficulty breathing which required hospitalization (and thus lead to costs). However, SDS may not be the only factor in the hospitalization and therefore untangling the costs that can be attributed to SDS becomes difficult.

Another human impact of SDS is the loss of life or increased care for people injured in transport accidents, most often air- or land-based in nature. Calculating the economic impact is challenging, as there is a need to consider the health impacts (fatalities, injuries) as well as the loss of goods and services due to the accident. While an accident itself may be very location-specific – for instance, closing a section of a major highway – the knock-on effects on changes in traffic patterns (for example, redirecting commercial trucks onto alternate routes) can be hard to capture using available data.

Finally, the health conditions triggered by SDS events will vary across populations, due to factors such as gender, age, income and wealth, nutrition access and availability, as well as the ability to avoid dust events through housing and/or ventilation. Distinguishing these variations in conditions of SDS-affected individuals can be difficult when the data available is limited in coverage or detail.

6.5 Identifying the damage and costs of SDS

6.5.1. On-site costs – economic activity

On-site damage is usually in the form of loss of soil and sand, which leads to scalding[1] of the site. Associated with the loss of soil or sand is the loss of soil nutrients and organic matter including soil carbon (Leys and McTainsh, 1994; Leys, 2002). This loss of soil or soil nutrients reduces the productive capacity of the soil, and thereby potentially reduces the income for landowners or land users, with the impact varying based on the location, economic and political context of the region (Economics of Land Degradation [ELD] Initiative and United Nations Environment Programme [UNEP], 2015).

Further costs are incurred in the source region due to damage to infrastructure such as irrigation or water systems, destruction of fences, loss of livestock and forage for livestock, sandblasting of crops and road cleaning. Dust can also contain soil carbon, which could have a value to the landowner, particularly if in the future carbon sequestration and carbon markets become more functional.

Huszar and Piper (1986) suggest that an approximation of the immediate on-site costs of wind erosion, such as damage to infrastructure, can be obtained from the off-site costs. Using the method proposed by Huszar and Piper (1986), a value of 2 per cent of the costs of household cleaning can be used as the basis for determining on-site costs based on the calculations.

Using this method, Tozer and Leys (2013) estimated on-site costs of approximately $A 5.1 million for a single severe dust storm that affected eastern Australia in 2009. The estimated cost was consistent with the Natural Disaster Relief Assistance request of $ A4.5 million to compensate landowners for costs and losses due to the event (Kelly, 2009).

However, the method used by Huszar and Piper (1986) does not account for the long-term loss in productivity or income due to soil erosion and soil nutrient loss, and may only be appropriate in situations where productive land is the source area, such as in remote grazing regions, like central Australia or the southwest of the USA. ELD Initiative and UNEP (2015) provide an approach that can measure the loss in production and income due to soil erosion in general, but the methodology can be applied to countries where SDS originate, as some of the losses in soil and/or sand are due to anthropogenic activities, such as agriculture or deforestation.

6.5.2. Off-site costs – economic activity

Off-site costs of SDS will depend on many factors, with the principal factor being the level of economic activity in the impact region. For example, SDS that affects mainly agricultural or pastoral regions may not have as much economic impact as SDS that affects a major metropolitan area. The main reason for the difference in impact across different regions can be attributed to the level of infrastructure in the different regions and the relative populations.

Major urban centres are more affected by SDS than less populated rural areas. This is simply due to the higher amount of the population that are subject to health impacts, the level of wholesale, retainment of commercial and industrial activities, and disruptions caused by SDS impacts on traffic or the provision of education due to school closure or restriction of outside activities in these urban areas. Implicitly included in the costs incurred within many sectors, including commerce, manufacturing, transport and the public sector, is the cost of cleaning or removal of sand and/or dust from impacted locations.

1 See https://www.qld.gov.au/environment/land/management/soil/erosion/types for a definition.

Transport

Major cities tend to have more key transport infrastructure than regional centres, including airports and airline hubs with significantly higher aircraft movements, rivers, seaports and road transport systems. Any factor that limits capacity or vehicular movement can cause substantial economic losses.

Costs to the various transportation subsectors vary due to the types of impacts. The airline industry is affected as SDS typically reduces visibility, making landing and taking off difficult. This can lead to aircrafts being grounded, leading to flight delays, cancellations or diversions.

An SDS event can have several impacts. Airlines will lose income through reduced passenger numbers, with some passengers receiving fare refunds. Aeroplanes will need to be diverted if they cannot land at an affected airport. Following diversions and delays, aeroplanes will need to be repositioned to ensure the schedule returns to normal after the SDS event.

In some cases, airlines will provide food and/or accommodation for passengers that are affected by delays or cancellations or provide alternative means of transport to their final destination (Williams and Young, 1999; Tozer and Leys, 2013).

Although water transport may not be as severely affected by reduced visibility as the airline industry, it may cause port and ferry services to be reduced (Tozer, 2012). Also, port services may be affected through increased loading or unloading times due to worker health and safety issues. For instance, dust may cover surfaces, making them unsafe to work on. A reduction in port processing time could add costs such as demurrage to the total costs for a ship owner or charterer.

The impact on the road system can be a significant cost. The effects of SDS on road transport are:

- **road closures due to either visibility or dust or sand on the road surface**
- **traffic accidents due to surface or visibility conditions**
- **reduced transport requirements as a knock-on effect from reduced activity in other sectors, such as the construction industry**

Dust storms have been shown to directly lead to traffic accidents in, at least, Australia, Iran and the USA (Williams and Young, 1999; Burritt and Hyers, 1981; Miri et al., 2009).
Two aspects that can affect the costs of road transport are:

- **travel speed during SDS**
- **the number of vehicles on the road during an event**

These two aspects affect travel time for road users. Travel speed may be reduced due to poor visibility during a dust storm, but if some employees or parents remain at home during the event, the number of vehicles on the road system may be reduced (Tozer and Leys, 2013). As a result, the impact on travel speed and transport costs may be difficult to estimate.

Health

The health impacts of SDS are difficult to measure and to assign a cost to, due to the differences in reporting across countries or regions and differences in analyses of data. In a review of 50 papers reporting health effects due to dust or poor air quality, de Longueville et. al. (2013) found mixed results as to whether health was impacted by atmospheric dust or poor air quality.

One issue that arises in much research related to the health impacts of dust is attribution of effect. For example, an at-risk portion of the population, especially those with pre-existing cardiopulmonary issues, may have a higher mortality or morbidity rate during a dust storm due to the atmospheric dust exacerbating the pre-existing condition.

The issue then becomes whether the dust is the cause of the mortality or morbidity or simply the final contributor that leads to the death (de Longueville et al., 2013). Huszar and Piper (1986) estimated that the health costs to households of a series of SDS events were approximately US$ 19 million out of the total household cost budget of US$ 458 million. Tozer and Leys (2013) did not find any significant health effects of the Red Dawn event in Australia in 2009, but this may be at least partially attributed to an early warning system in place for at-risk populations. However, the health costs estimated are only the direct costs to households and do not capture the effects on society of reduced health due to SDS.

Household cleaning

Previous research has shown that households face the highest direct costs of SDS due to interior and exterior cleaning, as well as repairs and maintenance of structures and vehicles (Huzsar and Piper, 1986; Tozer and Leys, 2013). Miri et al. (2009) found that household cleaning costs accounted for over 85 per cent of the total costs estimated for dust storms in the Sistan region of Iran. In assessing household cleaning costs, the value of time and resources used, as well as income opportunities lost or deferred, need to be understood in terms relative to the economy and level of income where these actions are taking place.

In many cultures, household cleaning is a task allocated to women and girls. The additional work needed to clean up after an SDS event could increase overall workload for women and girls and reduce opportunities to otherwise gain income or non-monetary assets (for example, from the collection of natural resources).

Commerce and manufacturing

Measuring the effect of SDS on the commercial sector is fraught with challenges. Some expenditure that is not made during an SDS event may be made after, meaning that there is no loss in income for some commercial operators. This is especially true for food and essential items purchases made by households, as the purchases are simply delayed rather than not made, and only delayed for the duration of the event.

However, time-sensitive purchases, such as newspapers and perishable or fresh foods like bread or fruit, may not occur during the SDS event. The absence of these purchases will cause retailers to lose revenue and the product(s) to be discarded. Similarly, discretionary purchases by consumers, such as takeaway coffee, may not be made, again reducing retailer income (Tozer and Leys, 2013). Other indirect costs may be incurred in the commercial sector due to delays in delivery of goods required for production or movement of goods out of production facilities.

The manufacturing sector may be affected by SDS if the particulate matter enters the manufacturing facility, or through delays in material required for production being held up in transit. For example, electronics component manufacturers in Korea noted that on days of high particulate matter, more faulty products or faults in final components were observed (Kim, 2009).

Another cost of SDS in the commercial sector is that of absenteeism, or employees being absent to care for children (if schools are closed during an SDS event) or others in need of care. Absenteeism has been shown to reduce productivity, and as a consequence of the SDS event, must be added to the cost. A point to consider is that only the loss of productivity should count towards costs incurred as a result of the SDS event, as costs of production should include costs of workers taking leave for various reasons (Tozer and Leys, 2013).

Agriculture

SDS can impose costs on the agricultural sector through:

1. Crop destruction or reduced yield
2. Reduced animal production due to animal death or lower yields of milk or meat

Ai and Polenske (2008) estimated that the impact of SDS on the agricultural sector in the Beijing region in 2000 was the second highest only to the manufacturing sector and constituted about 36 per cent of the total cost in that year.

For annual crops, losses are due to sand or wind blasting and can lead to complete loss of crops in a particular region or a reduction in yield due to partial losses. The impact on perennial crops could be similar to annual crops in that the current year crop could be lost or reduced. However, there may also be a longer-term effect on some perennial crops due to tree or crop damage (for example, Lucerne/alfalfa crowns being damaged), leading to reduced production in future years.

Animal production can also be affected in several ways. There may be a reduction in milk produced during the SDS event, thus costing the producer income with no compensatory reduction in costs. The SDS may lead to the loss of animals, either through death (particularly through suffocation in severe events) or through producers being unable to locate them after they fled the SDS event. An animal producer may also face lost, destroyed or damaged feed stocks, pasture or forage crops, requiring the producer to purchase feed that they would otherwise not have done.

Other costs

Other costs of SDS in the impact region include:

1. Reduction in construction and mining activity, due to health and safety issues at the construction or mine site
2. Increased emergency service activity, due to road or traffic accidents or ambulance traffic transporting patients to hospitals due to dust-related health problems
3. Damage to utility infrastructure such as electricity transmission lines or pylons

In some cases, SDS may lead to damage, but there may already be pre-existing conditions that contributed to the final damage caused by SDS.

SDS can also impact cultural, leisure and sporting activities and the cost to the economy will depend on the type of event affected. Estimating these costs can sometimes be difficult, particularly if the event is a one-off event such as an outdoor music concert.

The closure of schools and educational establishments due to health concerns can also impose costs on the economy. However, many of the costs will be captured in other estimations.
The costs of carers remaining at home because of SDS events will be captured in the absentee estimation and reduced transactions at commercial establishments will be gathered in the retail/wholesale sector calculation.

As noted earlier in **chapter 6.2,** there are different costs associated with SDS, and there are also different or more appropriate valuation methods for some of these costs – market or non-market valuation. **Table 7** presents a brief overview of some of the costs covered earlier in this section and appropriate methods of estimating or valuing these costs. For some costs, such as health or water resources, the total impact of costs may be estimated using a combination of methods, due to the differing impacts across sectors and the population.

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6.5.3. Off-site benefits

Typically, there are few immediate benefits offered by SDS events, and in the context of the overall costs and benefits of SDS, off-site benefits are usually relatively small when compared to off-site costs. Benefits of SDS arise from two main sources – nutrient deposition on land and nutrient and mineral deposition in water, particularly ocean bodies.

SDS dust content can contain soil nutrients, such as nitrogen, phosphorus and potassium, as well as organic carbon. When deposited, these can provide nutrients to crops or pasture downwind of the source area. Leys (2002) estimated that dust deposited after a dust event contained 0.0034 g/m^2 of total nitrogen and 0.0008 g/m^2 of total phosphorus. Nutrient and mineral deposition in ocean bodies can provide nutrients to phytoplankton, which in turn can increase fish stocks, as phytoplankton are in the lower levels of the ocean food chain (Cropp et al., 2005).

The benefits of soil carbon deposition are more difficult to estimate due to the need for a value for carbon in the system where the deposition occurs. The challenge in terms of estimating the benefits is determining the overall dynamics of the food chain and the time for any increase in phytoplankton to flow through to the upper levels of the food chain where economically viable populations of fish are located. Iron contained in dust can also lead to increased carbon sequestration by phytoplankton as well (Blain et al., 2007). Again, the amount and value of carbon sequestered is difficult to estimate and beyond the scope of the current study.

One point to note here is that some degree of dust movement is an integral and natural part of the earth system. This deposition brings benefits as well as hazards to human communities (Middleton and Goudie, 2001). Total removal of dust movement is undesirable and probably extremely costly in terms of ecosystem losses.

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Table 7. Examples of costs and valuation methods for measuring impacts on various economic activities

Economic activity	Cost type:		Valuation type:	
	Direct	Indirect	Market	Non-market
Transport	Airline delays and cancellations	Rail or road delays due to closures	Usually market-based	
Health	Hospital admissions	Decrease in health of individuals over time	Direct expenditures on health-related costs	Mortality or morbidity costs on society – can use disability-adjusted life years or other measures but not market-based measures
Cleaning – Household and commercial	Direct cost	NA	Market costs of product and time	NA
Commercial or manufacturing	Loss of sales or production during dust event	Reduced, or loss of, sales due to inability to get product to market or get inputs into manufacturing plants	Market costs of lost sales in both direct and indirect cases	NA
Agriculture	Loss of marketable product; delays in harvesting at optimal time	Delayed regrowth of perennial crops, or loss of product due to delays in planting at optimal time	Market costs of lost production in current or future crops	NA
Water resources	NA	Dust deposition in water ways, i.e. rivers, canals etc.	Cost of dredging or dust/mud build-up	Losses in services in the future, such as water access or availability; effect on fish or other populations affected by build-up
Ecosystem services	Loss of use during event	Dust deposition in ecosystem, i.e. on plants	Loss of income by service providers	Most costs will be valued using non-market techniques, such as travel cost or contingent valuation methods

6.6 Methods to assess the economic impact of SDS

6.6.1. Overview of model types

The assessment of the economic impact of SDS can be undertaken using a variety of methods, from relatively simple accounting-type methods to more complex econometric or mathematical programming models (Cochrane, 2004).[2] The methods can be categorized as follows:

- combined econometric and optimization models – computable general equilibrium (CGE), partial equilibrium (PE), or other generic econometric and simulation models
- linear programming models – Input-Output (I-O) models
- survey methods and analysis
- accounting-type models
- hybrid models

These models have been used to measure the economic impact of SDS or other disasters. Their applicability or usefulness in assessing the economic impact of SDS depends on available data, the type(s) of event, and assumptions made. Table 8 briefly summarizes each methodology, data requirements and analytical skills required to undertake an economic assessment of SDS using each methodology.

Computable general equilibrium (CGE) models have been used to analyse the impact of disasters on economies but have not been used to study SDS impacts (see, for example, Rose and Lim, 2002; Rose and Liao, 2005). As the name implies, CGE models are models of a whole economy, including households, firms and government (through taxation submodels).

The model is based on the social accounting matrix (SAM) for that economy. A SAM captures all the interactions between the various industry sectors within an economy, including households, firms or businesses, and where necessary, governments through the impact of taxation on costs of production and incomes.

These types of models rely heavily on the parameterization of the models and price changes to measure the impacts of perturbations to the economy, such as disasters or changes in taxation policy, and how they affect the whole economy. However, the impact of SDS on prices or changes in interactions between sectors, as measured by the SAM, is difficult to do given the frequent nature of SDS events, within a year and over many years (Cochrane, 2004).

Input-Output (I-O) models, which are similar to the CGE models, rely on the SAM to measure the interactions between industry sectors. As a result, they have very limited flexibility to deal with changes that occur within a year – changes which may not significantly impact interactions between sectors.

Another problem with CGE or I-O models in the analysis of SDS is that to measure the impact, the SAM or parameters of the model rely on changes from a base scenario which is perturbation-free. However, as noted earlier, because SDS occur frequently within and across years, identifying a counterfactual base is very difficult.

One aspect that the SAM – and therefore I-O or CGE models – does not capture due to the non-market valuation is the value of the environment or ecosystem services, except through transactions such as cleaning costs or travel costs to an environmentally sensitive destination. These types of models do not typically have the ability to capture the impact on humans of SDS, either through mortality or morbidity or changes in the distribution of wealth or equality.

2 A full comparison and motivation for any one type of model is beyond the scope of this chapter. Readers interested in a more complete discussion should consult the references provided at the end of the chapter.

If measuring the impact of SDS across a region, either within a country or across several countries, a model of the region or each country in the region is required. In some countries these types of models are available, for example, studying the effects of SDS on Beijing, Ai and Polenske (2008) used a regional I-O model to estimate the impact of SDS.

Surveys have been used in previous analysis of the impact of SDS (Huszar and Piper 1986). Surveys are typically limited to certain segments of the economy, such as households or businesses, and may not capture the interrelationships between industry sectors.

However, surveys are useful in identifying specific costs or types of costs, as shown by Huszar and Piper (ibid.), who surveyed households and businesses in the state of New Mexico in the USA and identified household costs down to specific categories, such as exterior painting, landscaping, interior cleaning and laundry, and automotive damage. However, Huszar and Piper (ibid.) did not survey transportation agencies or firms, or public agencies such as the state Department of Transport or the emergency services. Therefore, the costs of the dust storms may be underestimated.

Tozer and Leys (2013) and Williams and Young (1999) used an accounting-type framework to estimate the costs of dust storms in two Australian states. The studies utilized the survey data of Huszar and Piper (1986), adjusted for the situation and differences in frequency of SDS and exchange rates, to measure some of the impacts of SDS.

This approach requires complete identification of all costs and the ability to source the required data to enable full costs of SDS to be measured. Also, this type of analysis needs to ensure that interactions between sectors of an economy are captured. Care needs to be taken to ensure double counting of costs is avoided (Cochrane, 2004).

Cochrane (ibid.) identifies one other type of tool to analyse the impact of natural disasters, and this is what he terms "hybrid models". These types of models are usually disaster-type, case, country or region-specific and are criticized for being somewhat ad hoc.

An example of this type of model provided by Cochrane (ibid.) is the HAZUS model that is used to simulate indirect economic losses from natural disasters such as floods or earthquakes in the United States. Cochrane (ibid.) indicates that hybrid models can also include combinations of two of the model types discussed earlier, providing they are well constructed and allow for sound loss accounting, and that they are reasonable models to use in calculating economic costs of natural disasters.

6.6.2. Data requirements

One crucial aspect of selecting a tool to analyse the economic impact of SDS in a country or region is the availability of the required data. Where possible, the data used should enable a disaggregation of impacts by gender, age and disability.

Techniques such as CGE or I-O require sufficient data to construct the SAM, therefore data that shows all the interactions between segments in the economy is needed. This implies that significant industry level data are required as being able to measure the interactions between sectors and measuring the substitutability of production across sectors is a requirement for the SAM. Other methods, such as the cost accounting or survey method, do not require as much data as CGE or I-O, but do still require significant amounts of data, some of which can be difficult to identify and collect, such as household costs, reductions in retail sales, or consumer willingness to pay for environmental damage.

For the accounting method that uses survey data – or the survey method itself – it is necessary to identify the survey population, and from within that population, the survey sample. This should inform the design of the survey, which also requires a pilot test. Then, the data must be collected and analysed.

A similar approach is required for the non-market valuation studies, in that surveys or other similar research tools need to be developed to collect the required data to value environmental or ecosystems loss or damage.

Table 8. Summary of methodologies, data requirements and skills required

Impact methodology	Data requirements	Analyst skills	Strengths of method	Weaknesses of method	Applications to sand and dust storm impact analysis
Computable general equilibrium (CGE)	Very high – need data set including the entire economy.	Very high – need to be able to construct a social accounting matrix.	Good for single event analysis.	Need a control year.	No applications to sand and dust storms. Has been applied in single event disasters: Rose and Lim (2002), California earthquake; Horridge, Madden and Wittwer (2005), Australia drought.
Input-Output (I-O)	Very high – need data set including the entire economy.	Very high – need to be able to construct a social accounting matrix.	Good for single event analysis.	Need a control year.	Ai and Polenske (2008), impact of sand and dust storms on Beijing.
Surveys	Medium – need a good response rate to surveys.	Medium, but high with respect to survey design and sample selection.	Simple; easy for low-skilled analysts. Can extrapolate single events to multiple events.	May be costly to gather sufficient quality and quantity of data for complete analysis.	Huszar and Piper (1986), impact on New Mexico of multiple sand and dust storm events.
Hybrid	Medium–high.	Medium–high – need skill to identify data and data gaps.	Relatively simple; can capture whole impact, providing there are no data gaps. Can extrapolate single events to multiple events.	If there are data gaps or poor data-collection, very poor results.	Tozer and Leys (2013), Single event sand and dust storms in Australia; Miri et al. (2009), multiple events in Sistan region of Iran.

6.7 Factors to consider in selecting ways to measure economic impacts of SDS

6.7.1. Challenges to be addressed

The principal challenge in measuring the economic impact of SDS is not the physical, that is, not the type of SDS event or the geography or geology of a region or country. The main challenge is ensuring all relevant and consistent data are identified and collected, and that the economic impact is measured relatively accurately.

It must be remembered that any measure of economic impact will be an estimate. Any measures of impact will have some degree of error due simply to the data-collection and analysis process, and the time delay for some impacts to flow through an economy.

The more differentiated economic activity is within a country, the more data are required to fully measure the impact of SDS. One point to consider here is that SDS may not impact all economic sectors in an economy or a country due to the geographic concentration of SDS, thus reducing the need for a full set of economic measures or data for the whole economy, only those sectors impacted.

Another limitation to identifying an appropriate method of impact analysis is the available skill set of analysts within a region and existing economic models. If a country has the capacity to collect sufficient data or the skill set to construct a SAM and therefore a CGE or I-O model – which would be ideal for a single-event SDS – then a simpler method, such as surveys or a hybrid model, is required.

Another determining factor in the selection of an appropriate method for impact assessment is the budget available for the analysis. Undertaking a comprehensive survey of an economy is an expensive operation. The amount of data that can be collected using a survey or set of surveys may be a limiting factor.

6.7.2. Recommended approach

Given the diversity of resources to collect and analyse SDS economic impact data across countries, the recommendation here is that a relatively simple approach be taken. The preferred method is a hybrid of cost accounting and surveys, where surveys are used to identify costs that may not be readily available, such as household cleaning costs. Another reason for recommending this method is that it will allow cross-country comparisons, as all countries or regions will be using the same framework.

As noted throughout the preceding discussion, availability and consistency of data can be problematic when undertaking impact analysis, and also when comparing across events within a country or across countries. Another issue that arises with data-collection, and indeed impact assessment, is that of timescale and estimating the impact of multiple events from single-event data.

It is recommended that a consistent method of data-collection be utilized to ensure valid and relatively accurate data are collected. This will also allow valid comparison across countries or regions. A comprehensive set of guidelines for data-collection and data sources are provided in **chapter 6.13**.

One significant issue with respect to impact of SDS is related to the effects of SDS on human health and the attribution of an SDS event to mortality and morbidity in the impact region. It is recommended that research be undertaken to accurately measure the impact of SDS events on human health, and that this research properly identifies the true impact of SDS on human health. This implies that research must be comprehensive, beyond simple correlation analysis of hospital admissions and SDS events, that prior health status must be identified and that demographic variables such as gender, income, age, household location and construction must be fully captured in the data-collection and analysis.

6.8 Benefit-cost framework for analysing dust mitigation or prevention

6.8.1. Basic construct of cost-benefit analysis

Benefit-cost analysis (BCA) or cost-benefit analysis (CBA) is a method of analysis that is used to compare the investment value of different projects.[3] Cost-benefit analysis is a form of investment analysis that takes into account current and future costs and benefits associated with a project to estimate the net present value (NPV) of the project. Using NPV as a basis of comparison allows decision makers to evaluate projects that may have different income or cost flows throughout the life of a project.

An NPV model for a proposed dust-mitigation programme could take the following form:

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{(R_t - C_t)}{(1+\rho)^t}$$

Where:

- C0 is the initial cost of the mitigation investment
- Rt and Ct are the revenues and costs generated from the mitigation programme
- t = 1 to T are the number of time periods in which the investment is measured.
- p is the discount rate and measures the time value of money

For example, NPV can be used to compare two projects:

- one with a high initial cost and a long period before income is received, such as planting a forest
- one with smoother income and cost flows, such as an annual cropping programme

The main difference between CBA and NPV investment analysis is that CBA extends NPV by adding non-market information to more extensively capture the true value or full costs and benefits of a project (Hanley and Spash, 1993). This extension allows policy and decision makers to understand the implications of including non-market information, such as the value that environmental or ecosystems services have, on a project's total benefits and costs. One aspect that is not captured in CBA is the equality or distribution of wealth in different socioeconomic classes and how proposed investments affect these different groups (Wegner and Pascual, 2011).

CBA proceeds in a series of stages in a process which is fairly linear, although all stages may be overlapping in some sense.

3 A full description of the basics of 'cost-benefit analysis' and 'net present value' is beyond the scope of this chapter. Interested readers are referred to Harris (2006), Hanley and Spash (1993) or Robison and Barry (1996) as starting points for descriptions of the two methods.

Stage 1 is simply identification of the project, where:

- the first component is the resources that will be reallocated in the project – this includes financial and physical resources
- the second component is identification of the impacted populations, including both positive and negative impacts

Stage 2 is to identify the impacts of the project on reallocated resources. These impacts can be physical or financial – the reduction in dust emission and the costs of this reduction at the emission source, as well as the changes in the environmental services that occur because of the project.

Stage 3 involves identification of the economically relevant impacts. This may sound redundant, as most costs or benefits from a project will be economically relevant, but a major discussion in the economics literature concerns the inclusion of transfer or compensation payments. This will be discussed in more detail in a later section, but a brief précis on the context of SDS and compensation may be helpful.

For example, if a dust-mitigation project generates a net-positive benefit across a region, this indicates that the project is feasible, even if one of the impacted populations is negatively affected and another population is positively affected. The positively affected population could compensate the negatively affected population to balance impacts. However, in the context of CBA, this is considered a transfer payment and is not included in the "benefits" of the project.

Stage 4 is the physical quantification of impacts. This stage is critical, as quantifying the timing of these impacts is also measured. At this stage, if necessary, uncertainty can be included in the calculation of impacts, either physical or financial.

Stage 5 is the valuation of the impacts. At this stage, valuation includes taking into account the time value of money from Stage 4 when impacts occur. "Time value of money" takes into account the fact that, in theory, money loses value over time, so a dollar today is worth more than a dollar tomorrow. As a result, investors or project managers prefer higher returns earlier in a project than later.

6.8.2. Costs and timing of costs in cost-benefit analysis

Costs incurred and timing of costs depend on selected practice. For example, undertaking an annual cropping programme to provide some surface cover to reduce soil erosion will incur annual costs for seed, fertilizer, chemicals and pesticides (if used), some form of mechanization (machinery or draught animal) for ploughing, sowing and – if necessary – harvesting and labour required for all activities including sowing, harvesting, storage and transport. All these costs will be incurred each and every year of the farming programme.

If the preferred choice is to use some form of forestry for dust mitigation, a large investment is required in the first year for land preparation and tree planting. A lower cost may be incurred in the year immediately after planting the trees for activities such as weed control or irrigation of the young trees to ensure their survival. In subsequent years, very few costs will be incurred, as the trees require little maintenance, assuming long-term irrigation is not necessary. The level of maintenance costs incurred will depend on whether the forest project is a permanent forest or a harvested forest.

If the forest is to be permanent (not harvested), little maintenance is needed beyond the initial year or two. If the forest is to be harvested and replanted, then regular maintenance will be required for activities such as trimming and thinning to ensure a profitable crop can be harvested.

6.8.3. Discounting and the discount rate

When analysing investments over time, it is necessary to convert future costs and/or benefits to current values so that comparison of investments is undertaken in a standard value. To undertake the conversion, future costs or benefits are “discounted” by the discount rate, $\rho\,(0 \le \rho \le 1)$.

The discount rate is a measure of the time value of money. Higher discount rates imply that the time value of money is high, so income is preferred earlier rather than later in the life of an investment. A discount rate of zero implies that there is no time preference for income.

Selection of the discount rate depends on the risks involved, the current inflation rate, cost of money (the interest rate), and whether there is an additional consideration of the social rate of time preference (Harris, 2006). The selection of an appropriate discount rate for analysing a mitigation project is a critical decision and should not be made lightly. Selecting an inappropriate discount rate for project comparison can make a project appear to be more or less preferable, as the discount rate affects the current value of costs and benefits over the life of a project, and the current values change with different discount rates.

6.8.4. On-site benefits of dust mitigation at the source

On-site benefits can come from several sources. The first is relatively simple – the crop or timber can generate income, if that is the practice selected. However, timing of the income will differ depending on the practice chosen.

For an annual cropping programme, income will be received every year, where income will be a function of price and yield. For a forest, the majority of income will be received when the forest is harvested, with potentially some income in years when the forest is thinned.

The second source of benefit is through costs saved in the cropping programme through reduced soil erosion that can maintain or even increase crop yields, and loss of soil nutrients through dust emission to the atmosphere. In some cases, there may appear to be no obvious on-site benefits, but there may be some less obvious benefits. For example, a sand dune stabilization project may appear to have no on-site benefits, but if the stabilization project reduces dune encroachment on a road, then there is an on-site benefit.

6.8.5. Off-site benefits of dust mitigation at the source

Off-site benefits of dust mitigation are numerous, with the benefits contingent on the impact region, economic and environmental infrastructure and activity within that region, and the level and type of dust mitigation achieved in the source region. As discussed in earlier chapters, SDS affects many sectors of the impact region, thus any reduction in either frequency or severity of SDS or the amount of dust deposited during SDS may be beneficial. However, measuring the benefits can be difficult. Unless SDS are completely eliminated, there will still be some negative effects on the impact region.

6.8.6. Off-site benefits of dust mitigation in the impact region

Different types of mitigation processes can be undertaken in the impact region to reduce the effects of SDS. These include early warning systems or mechanical aids such as air filtration systems or improved building construction to reduce dust entering buildings.

Again, it may be difficult to measure impact, as only those segments of the population that are affected by SDS may take advantage of the early warning system or improve the construction of their home so as to reduce the impact of dust on their family. However, there is some indication that early warning systems for vulnerable segments of the population can reduce the effects of SDS.

Tozer and Leys (2013) report that during the Red Dawn event in 2009, affecting Sydney and other parts of eastern Australia, there was no significant increase in hospital admissions. They attributed this to a health warning system that sent SMS messages to those in the population with respiratory problems who had subscribed to the system. One point to remember here is that mitigation programmes or early warning systems in the impact region do not reduce the amount of dust impacting the region, they simply reduce the impact of dust on the region.

6.9 Non-market valuation methods for inclusion in cost-benefit analysis

The major challenge in CBA is estimating costs and/or benefits for attributes that may be impacted by SDS but have no identifiable market value or method to value them using market-based techniques, such as environmental benefits or ecosystem services. There are two classes of non-market valuation techniques: (i) revealed preferences and (ii) stated preferences.

- **Revealed preferences**, as the name implies, are modelled on actual behaviour, typically purchase or demand behaviour, that is, how and on what consumers spend their money (Just, Hueth and Schmitz, 2004).

- **Stated preferences** are based on what consumers say they are going to do, usually shown by survey responses (ibid.).

Within these two classes are different methods for revealed preferences. There is hedonic pricing and the travel cost method, and for stated preferences, contingent valuation and choice modelling.

A final category of valuation is to use some form of experimental analysis to identify the “value” for the “service” provided. Each of these different methods can be applied to various non-market issues arising in CBA of SDS mitigation strategies.
The literature on valuing ecosystem services – or for other system attributes which have no discernible market – is vast and comprehensive. See, for example, Ninan (2014) and the references and examples contained therein. From the perspective of CBA, the following techniques are presented as potential methods of valuation. As a full explanation of the techniques is beyond the scope of this chapter, readers are directed to the references section as a starting point for further information on methods discussed herein.

6.9.1. Hedonic pricing

Hedonic price analysis treats a “product” not as a single product but as a collection of attributes, qualities and characteristics which consumers desire and for which they are willing to pay. The price a consumer pays for a product reflects how they “value” each attribute of that product (Costanigro and McCluskey, 2011).

When a consumer purchases a car, they are purchasing the set of attributes contained within the car – safety features, colour, engine capacity, number of seats, brand and reputation, among other attributes. Some car brands are more expensive, such as Lamborghini®, and some are relatively inexpensive, such as Nissan®.

Consumers will pay more for the Lamborghini® because they are willing to pay more for the set of attributes associated with that brand rather than the Nissan®, even if the primary rationale for a car as a means of transport is the same for both brands. The application of hedonic pricing in CBA of SDS is relatively limited as there are few “products” involved in SDS mitigation that could be analysed in this way.

6.9.2. Travel cost method

The travel cost method uses consumer behaviour to measure the value consumers place on “goods” such as environmentally or culturally significant sites (Hanley and Spash, 1993). The method measures how much consumers are willing to pay to “travel” to a site, where paying includes travel costs, such as flying or driving, entry fees, accommodation costs, capital equipment (for example, camping gear), and on-site expenses such as food and drink. By summing the travel costs across the expected number of visitors to a site, the “value” of the site can be estimated.

6.9.3. Contingent valuation method

The contingent valuation method (CVM) uses surveys of consumers, usually in some form of controlled experiment. They are asked how much they would be willing to pay for a particular product or service with specific attributes. In ecosystem or environmental analysis, “consumers” are asked how much they would be willing to pay for the services provided by the ecosystem or environmentally sensitive area, or alternatively, they are asked how much they would be willing to accept for the loss of the services provided (Ninan, 2014).

6.9.4. Choice modelling

Choice modelling is similar to CVM, except that instead of valuing the service provided by the ecosystem or environmentally sensitive area, “consumers” are asked to value the specific environmental attributes of the area, then to choose between the alternatives that provide varying levels of the attributes (Ninan, 2014).

6.9.5. Experimental analysis

This method is used to address some of the shortcomings of the stated preference methods, such as the differences between what people say in the surveys, to determine willingness to pay and their actual behaviour, referred to as the “hypothetical bias”. In some experimental analyses, consumers use real money to determine a more accurate WTP. This can remove some of the hypothetical bias that may be apparent in survey responses in which there are no consequences for decisions made.

6.10 Examples of cost-benefit analysis for dust prevention or mitigation

There are numerous examples of SDS mitigation practices or restoration projects which are intended to address anthropogenic causes of SDS. The following are examples to demonstrate the application of CBA in measuring the costs, benefits, timing and location (on-site or off-site) of these costs or benefits, and other implications of the mitigation practice. The examples do not provide a comprehensive set of potential solutions.

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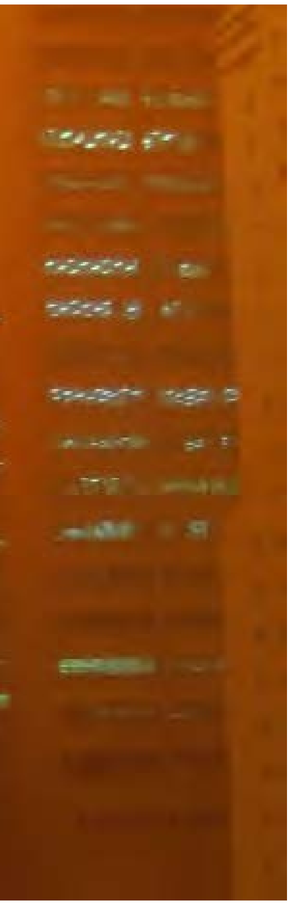
Any mitigation or restoration project needs to take into account local conditions such as soil type, water availability, aspect or topography on which to base the project design and the CBA process.

The four different scenarios are:

1. Land/soil surface mitigation through planting crops, re-establishing pasture or creating new pasture
2. Reforestation, including planning perennial tree crop
3. Off-site mitigation in the impact region.
4. Doing nothing

Note that “doing nothing” provides a comparison against the other three measures listed.

Each scenario will have a unique set of incomes and costs throughout the life of the project, which will affect the NPV of the project. Each scenario will also have different sets of non-market issues and income distributions.



One point to note here is that some of the following practices could generate benefits through carbon sequestration. However, due to a lack of well-established markets, these benefits may not currently be able to be measured, although they can be considered when markets are more established.

6.10.1. Land/soil surface mitigation

Pasture – No livestock grazing

If pasture or grasses are sown and **no** livestock are to be grazed then the on-site costs will be for the pasture seed and fertilizer, and any associated machinery or labour costs. The total costs of the pasture sowing project will depend on the area sown but will typically be incurred in the first year of the project, then some maintenance applications of fertilizer may be necessary in later years, and possibly permanent fencing to keep grazing animals out, if desired. There will be no on-site benefits except for the reduction in soil erosion over time.

Off-site benefits, which include the reduction of costs due to SDS, will depend on the area sown and the reduction in dust emissions from the source area (we also assume that there are no other mitigation practices undertaken in the impact region, thus there are no additional costs incurred in the impact region). One point to consider is that the full potential for reduction in dust emission may not occur in the first year of pasture development, as the pasture may take some time to establish and cover all exposed soil surfaces.

Pasture – Livestock grazing

The second option to allow grazing of the pasture once established. This will have a benefit in the source region, with income being generated by herders that use the land. If the “right” mix of pasture species is sown, soil erosion may be reduced and, in some cases, reversed. Similar to the “no grazing” approach, the benefits or reduced costs will depend on reduction in the amount of dust emitted from the source region.

In this scenario, pasture costs will be incurred in the initial year, and costs to purchase livestock – if not already owned – will also be incurred. Pasture maintenance and animal-related costs will be incurred in all years subsequent to the establishment year. Benefits will occur in each year that SDS impacts are reduced.

Annual cropping

An annual rain-fed planning system of one or several crops to provide soil surface cover or reduce the amount of soil lost through wind erosion can increase incomes in the source region and reduce costs in the impact region. In this scenario, the on-site costs may include crop seed and fertilizers, herbicides or pesticides, if needed, as well as labour (for sowing, crop maintenance and harvesting), machinery costs (if machinery is used) and costs of transport for taking a crop to market.

Assuming some or all of the crop is marketed, crop producers in the source region will benefit from the income. Both costs and income will be incurred and received in every year of the project. Similar to the pasture systems, benefits in the impact region will be due to the reduction in dust affecting the impact region. This reduction will be dependent on the amount of dust mitigated.

6.10.2. Reforestation

Non-harvested permanent forest

An alternative to annual cropping or animal enterprises is to establish some form of perennial crop, such as an agroforestry activity, or a perennial tree crop, such as an orchard or other plantation-type operation. The costs and benefits in these types of enterprises are very different to annual systems, in that a high establishment cost is incurred in the first year of the project, with no or very limited income in early years, while the perennials become established.

For a non-harvested forest, a very large investment cost is incurred in the first year of the project with the purchase and planting of trees, land preparation, and, if necessary, irrigation or some other form of water application system to ensure trees will grow. One significant cost in this operation will be labour for land preparation, tree planting and forest maintenance. Some costs will also be incurred in the years immediately after establishment to ensure the forest grows as desired and trees grow towards maturity. Given that the forest is not to be harvested, there will be no income derived from the forest itself, but other income may be generated if the forest is open to recreational activities, such as camping, hunting, walking, or harvesting mushrooms or wild plants.

The dust mitigation benefits of this type of practice will vary over the period until the forest becomes fully established. In the early years of the forest, dust mitigation may be relatively low as the trees will not provide sufficient wind speed reduction to significantly lower dust emission. As the forest matures, the reduction in wind speed will reduce erosion and subsequently reduce dust, which may be deposited in the impact region. In other words, the off-site benefits will be low in early years then steadily improve until the forest reaches maturity. Again, the scale of benefits will be contingent on the level of dust reduction due to the forest.

Commercial harvested forest

The initial costs of a commercially harvested forest will be similar to the non-harvested forest, as land needs to be prepared and trees planted. However, more costs will be incurred in subsequent years, as forest maintenance is required to ensure the harvested lumber generates higher income.

The other main difference is that income will be generated when the forest is harvested, and there is also potential for a small income to be generated from either sales of trees thinned to ensure high quality trees will be harvested at the end of the forest's lifespan or from charging for access to the forest to harvest wild plants. For the forest to continue providing a dust mitigation benefit, land preparation after the forest is harvested needs to incorporate dust-reduction measures and the associated costs.

The dust mitigation benefits in the impact region will also be slightly different than for the permanent forest. There may be periods during the forest establishment period when mitigation benefits are reduced while the new forest grows to a size in which dust emission reductions can be observed in the impact region. However, as with all dust mitigation strategies, the level of dust reduction in the impact region will depend on the scale of the forest project.

Commercial perennial fruit or nut orchards

In this scenario, the orchard is a commercial operation producing fruit or nuts. A higher initial cost would be expected as more infrastructure, such as a more extensive irrigation system, may be required, and fruit trees would be expected to be more expensive than forest species.

Depending on the fruit, nut or mix of fruit and nut trees, the income flow will vary somewhat, but it would be expected that the orchard would begin to provide economic levels of production within three to four years of establishment. This income would grow until the trees reach a mature size and steady production level by about year six or seven after planting. The cost structure for an orchard will also be different, as costs will be incurred in all years after establishment, even in years when the trees are not producing a crop, as they still need care and maintenance to ensure maximum possible crop production when they do mature.

An orchard will mitigate dust through reduced wind speed and soil erosion. However, similar to the forest options, the level of mitigation will be low in the years before the orchard reaches maturity. Again, the level of dust mitigation in the impact region will depend on how much dust emission reduction occurs in the source area due to the orchard.

One point to consider here is that it is possible to combine any of the options listed above to reduce dust emission from the source region. This may be a preferable option in regions where livestock raising is a main source of income, as trees, in the form of wind breaks or small forests, can be used to reduce wind speed across the soil surface and allow the establishment of pastures or annual crops. If developed with appropriate tree species, forests can also provide wood for fuel and dust mitigation if the trees can be coppiced for wood supply. Also, forests or crops can provide non-timber or non-food products such as medicinal products or raw material for further processing, such as tree saps.

6.10.3. Off-site mitigation

Governments, occupants or businesses in the impact region of SDS can undertake practices to reduce the impact of sand or dust on their region, lives or businesses. However, the key point here is that any practice will not reduce the level of dust deposited in the region, as the dust originates at the point of origin. Examples of dust mitigation practices include early warning systems. Warnings enable vulnerable segments of the population and important sectors of the economy to take action to reduce the impact of SDS on that segment or sector. In anticipation of warnings, building improvements, such as air filtration systems or installing tighter fitting windows and doors, can be used to reduce dust penetration into buildings or houses.

Early warning systems, in some form, can reduce the impact on important sectors. For example, in the transport sector, airlines can initiate programmes to reschedule or cancel flights before passengers arrive at the airport to board their aeroplane, thus reducing the costs of cancellation or incurring accommodation and other costs due to flight cancellation. Similarly, for road transportation, early warnings can be provided to those people planning on driving, and this may reduce road accidents due to the poor visibility caused by dust. These warning systems ensure that vulnerable segments of the population – such as those with respiratory or cardiovascular problems – remain indoors or in locations where dust levels in the air are relatively lower to reduce the probability of more serious health issues arising.

Construction or modification of buildings to reduce dust penetration is an option that has been used successfully in some regions of the world to reduce the impact of dust on processes or people. For example, Samsung® in South Korea modified their buildings' housing manufacturing processes to reduce the number of faults in components manufactured during SDS events (Kim, 2009).

The costs of the mitigation process will depend on the type of process. In the

case of early warning systems, it would be expected that governments would bear most of the cost, and the costs would depend on the type of system designed and implemented and the types of warnings given to the population. When individuals or firms choose to construct or modify buildings, then it would be expected that individuals or firms would be responsible for the costs.
As for the benefits of these practices, these would depend on the reduction in problems caused, such as reduced mortality and/ or morbidity, road accidents or flight cancellations. Through reduced costs, the benefits could also flow to private corporations, such as airlines, as the costs of flight cancellations or aeroplane repositioning may be reduced, due to the early warning systems developed and implemented. As noted above, the benefits of these types of approaches will be to the segments of the economy mostly at risk. There may be no reduction in other areas, such as road cleaning, due to there being no reduction in dust emission from the source area.

6.10.4. Doing nothing

While this may seem a trivial option, it is still an option in some regions or countries, simply because they may not perceive any benefits from incurring costs to reduce SDS, or they may think that the costs of reducing SDS far outweigh the benefits. Another issue that arises here – and which will be discussed in more detail in a later section – is that of transboundary issues, with respect to the distances dust travels from source region to impact region.

In the above discussion, most mitigation projects were in the context of anthropogenic sources of dust and can include water management projects. However, they may also include natural sources of dust that may be causing significant off-site costs, although these types of projects would need to consider natural cycles and what the implications would be if the source was mitigated.

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6.11 Issues in cost-basis analysis

There are several issues within the context of dust emission and mitigation practices that also need to be addressed in a broader context than the confines of the practices discussed in **chapter 6.10**. These include the:

- distributional effects of costs and benefits and the distribution efficiency of wealth and income of the proposed practices
- transboundary issues, particularly with respect to costs, benefits and potential compensation in the source and impact countries or regions
- land tenure issues, with respect to land being accessed or used in mitigation practices

6.11.1. Distributional efficiency

When analysing the results of a CBA for a proposed mitigation strategy, the benefits may outweigh the costs. Therefore, the strategy – from a purely economic perspective – is worthwhile (as the project is allocatively efficient). However, from a wealth distribution efficiency perspective, this may not be the case. For example, if the practice requires that previous users of the land be displaced, and their sources of income or wealth are reduced, then they may suffer losses of either income or wealth.

Even if there are sufficient excess benefits to compensate for this loss in the project, there may be no compensation forthcoming from within the project. This argument also holds if the "wealth" of the society is increased by the project, yet more landholders who are displaced have their wealth reduced after the project than those in the impact region who may have their wealth increased due to the project, resulting in a redistribution of wealth to the detriment of those in the source region.

6.11.2. Land tenure issues

One important factor contributing to the success or failure of a mitigation project relates to land tenure, and this is also related to the previous point regarding wealth distribution. Land tenure is important, as it has implications for the incentives to be provided to landowners to undertake any dust mitigation project proposed. For example, if a project requires that land be taken out of some form of production for a number of years, and that land is privately owned, then the landowner would need to be compensated in some form for the loss in income.

One type of land ownership that could create some issues in terms of desertification and dust mitigation is that of "commons", or common property, where land may be owned by government but access is unrestricted. Commons and access to commons can lead to the problem identified as "the tragedy of the commons" (Hardin, 1968).

In this research, Hardin (1968) discusses the implications for unlimited or unrestricted access to common property using a grazing common as an example. Without restricting access to the common, individuals will graze their own livestock without consideration of the behaviour of others, which in turn leads to overgrazing and degradation of the commons, which in the long run has a detrimental effect on everyone.

In terms of desertification and dust mitigation, commons may be a source area of dust emission due to overgrazing or the removal of tree cover for wood for fuel. Reducing access to users of the land may lead to reduced income or reduced wealth, as farmers may have to reduce stock numbers due to limited access to grazing.

In terms of dust mitigation projects, if part of the commons is to be utilized in a dust mitigation project, the question then arises as to what happens to those who were accessing the commons. Will they be compensated? If the area of the commons is reduced, will access also be reduced to ensure overuse does not occur?

Using a simple example may help in understanding the problem. Assume there is a commons of 1,000 hectares and that 1,000 sheep – owned by many farmers – graze on the commons, therefore the stocking rate is one sheep per hectare. If a dust mitigation project reduces the commons area to, say, 900 hectares, there are one of two potential outcomes for the farmers grazing their sheep on the commons: (i) the same number of sheep graze the reduced area, increasing the stocking rate to 1.1 sheep per hectare or (ii) the number of sheep is reduced to 900, to maintain the stocking rate at one sheep per hectare.

The questions that arise here are:

- How do policymakers reduce the number of sheep by 100?
- How do they do that equitably?
- Do policymakers then allow the extra stocking rate and potential overgrazing in the commons?

6.11.3. Transboundary issues – costs, benefits and/ or compensation

As noted earlier, transboundary issues are a common problem with SDS events, as dust can travel vast distances, crossing many national borders from the source to the final deposition region. Addressing or considering transboundary concerns in determining both the impact of SDS to begin with – and what the process may be for determining the process to be employed in developing and implementing dust mitigation strategies – is critical to the success of any mitigation practice.

For example, if dust is emitted from one region, without affecting that region except through the loss of soil and soil nutrients (as discussed earlier), then that region may not be willing to undertake mitigation, due to the costs of the proposed work, with potentially little benefit to that region. However, the countries in the impact region may offer to fund dust mitigation programmes, as there is a benefit to the countries providing the funds through a reduction of the cost of dust impacts.

One important issue with respect to transboundary issues is that of national sovereignty and how costs, benefits and compensation may affect sovereignty. For example, one nation that may be affected by dust may offer to help pay for dust mitigation in another, with the aim to reduce the effects of dust on the population of the donor country. This may need to be done in a manner which achieves the desired goal for the donor country but does not impinge on the recipient country's sovereignty. These types of issues could be addressed with tools such as debt-for-nature swaps (United Nations, 1997), whereby a country (or countries) in the impact region could reduce a source country's debt in exchange for that country undertaking a sand or dust mitigation strategy to reduce emissions.

6.12 Conclusions on cost-benefit analysis

The basis of CBA for measuring dust mitigation projects is relatively straightforward. However, there are several issues that need some structure. The most significant of these is non-market valuation – and selecting the most appropriate method of non-market valuation to measure costs and/or benefits in dust mitigation projects. In the case of the different costs and benefits of a mitigation project, there will more than likely be one more appropriate method of non-market valuation, but the most appropriate method will vary with the type of non-market problem being measured.

For example, ecosystem services can be measured using different methods, such as the travel cost or contingent valuation methods. The selection of method is somewhat determined by the main "user" of the ecosystem service. Thus, there is no definitive recommendation as to the "most appropriate" method of measuring non-market valuations across all types of costs and benefits, but researchers are encouraged to consult the extensive literature on non-market valuation techniques applicable to the type of cost or benefit being measured.

Also, as noted above, the selection of an appropriate discount rate is critical to measuring the net value of any mitigation project. The key recommendation here is that the discount rate should include investment costs and societal values – attached aspects of the mitigation projects. This is particularly important when measuring the costs and benefits of projects that impact or are impacted by non-market factors, such as ecosystem services or cultural locations.

The other main issue with respect to CBA is that of compensation and distributional efficiency. However, again, there is no definitive recommendation, as most of these issues are dependent on the affected population and on country policies. It would be preferable for distributional efficiency be taken into account when determining compensation or other effects of dust mitigation projects on the populations of the source or impact regions. Recommendations on transboundary costs, benefits and compensation are also not made due to factors such as national sovereignty and determination of appropriate methods for estimating costs or payments in dust mitigation projects.

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Box 12. Integrating gender into the cost-benefit analysis process

Gender considerations: A cost-benefit analysis can disaggregate costs and benefits according to different groups, including men, women, youth and people with disabilities, to better understand who incurs the costs and who enjoys the benefits from specific measures. A good gender analysis that identifies expected costs and benefits to men and women is a prerequisite for being able to value them on a disaggregated basis.

Why do it?

A cost-benefit analysis can help inform decisions about whether to proceed with an activity, decision or project and/or choose which option to implement. It can be particularly valuable for advocacy and communication to involve decision makers in finance and planning to demonstrate the expected social and economic returns associated with a project (i.e. for every $1 invested, how much society will benefit). A good cost-benefit analysis can expose the real (and sometimes hidden) costs facing women (for example, in terms of time spent working), and by demonstrating the economic return on these initiatives to society, support arguments for investing in capacity-building and support to women. Consideration of distributional issues within a cost-benefit analysis framework is also vital in terms of assessing the feasibility of options. If one particular group is disadvantaged by a proposed option, they are unlikely to support the initiative, which will undermine the achievement of results. Consideration of distributional issues therefore provides invaluable information on how project design should be adjusted to account for these factors.

When to do it?

A cost-benefit analysis can be used at various stages during the programme or project cycle:

- During the solution analysis and design phases, it can help inform the design of the project proposal and appraise the worth and feasibility (or otherwise) of the proposal(s).
- During implementation, it can check that the project is on track and inform any project design refinements and adjustments for the remainder of the project period.
- As part of an evaluation at the end of the project period, it can evaluate its performance or success. This can support transparency and accountability in reporting on how well funds have been spent and learning about whether a project
(or that type of project) is worthwhile and should be replicated.

Entry points for gender analysis

At the heart of the consideration of gender within a cost-benefit analysis framework is the treatment of equity and distributional impacts. The basic measure of overall benefits in a cost-benefit analysis reflects economic efficiency: $10 of benefits accruing to a poor farmer are treated the same as $10 of benefits to a wealthy hotel owner. In reality, societies commonly give greater weight to gains by disadvantaged groups. Consideration of how gains and losses are distributed is vital to ensuring that social equity is considered alongside economic efficiency.

In a cost-benefit analysis, the value of costs and benefits is determined by people's willingness to pay for (or how much they would pay to avoid) a good or service.

In reality, the willingness to pay is affected by the ability to pay. This means that the valuation of costs and benefits is based on the current ability of society to pay, or in other words, the current distribution of wealth in society, including existing inequalities in that wealth distribution.

A cost-benefit analysis is one tool that can feed into the decision-making process. Its results should be considered alongside other tools that examine equity and distributional issues in more detail.

Steps to incorporate gender into the cost-benefit analysis process

1. Determine the objectives of the cost-benefit analysis

Ensure that all relevant stakeholders (including men, women, elders, youth, children and people with disabilities) have fed into the decision-making process on which options to assess. Whose priorities are represented?

2. Identify costs and benefits – with and without analysis

When identifying the different costs and benefits and based on a good understanding of the underlying situation and problems, ensure that information on the distribution of those costs and benefits is captured and documented.

3. Measure, value and aggregate costs and benefits

When measuring, valuing and aggregating costs and benefits, ensure that no detail relating to the distribution of costs and benefits is lost.

4. Conduct sensitivity analysis

A sensitivity analysis tests the results of a cost-benefit analysis for changes in key parameters about which we are uncertain (for example, rainfall). If a sensitivity analysis alters the distribution of costs and benefits significantly, ensure that this information is captured.

5. Consider equity and distributional implications

This section should expose any equity or distributional issues related to the costs and benefits of different options and how they might affect the feasibility of the project. Possible approaches for maximizing benefits accruing to particular groups, including women, and measures for addressing any groups that are disadvantaged by the proposed options should be discussed.

Adapted from Vunisea, Aliti and others (2015). The Pacific gender & climate change toolkit. Secretariat of the Pacific Community. Available at https://www.pacificclimatechange.net/document/pacific-gender-climate-change-toolkit-complete-toolkit. Accessed on 17 July 2019.

6.13 Data-collection for assessing the economic impact of SDS

6.13.1. The need for good data

Good data are the key to assessing the economic impact of SDS. This data needs to include gender, age and health status of the individuals covered in any assessment.

The challenge for gathering good data is that some of the impacts of SDS are difficult to measure directly, such as household cleaning or impacts of mortality and morbidity in the population. Another challenge that arises is that of duration and frequency of SDS events, which makes estimating costs more difficult, as some costs are ongoing, and it is sometimes hard to clearly define costs incurred for each event. There are numerous sectors impacted by SDS events and the timing of some events can be especially costly, such as an event that occurs during flowering of a perennial tree crop or annual crop, reducing fruit set or total yield of a crop.

One of the challenges for data-collection for the purpose of measuring the impact of SDS is the timescale of data measurement. For example, given the infrequency of major dust storms in Australia, Tozer and Leys (2013) reported the impacts of a single major dust storm. However, as noted above, SDS events in other regions of the world occur on a more frequent basis, thus possibly making data-collection more difficult.

The other challenge for measuring impact is the determination of the effect of frequency of SDS in any one year on the overall economic impact. For example, data collected for one year in which there were few SDS events may underestimate the average economic impact across time and overestimate the impact if the data are collected in a year in which there were more frequent events. Thus, the challenge of scaling up or down due to timescale and frequency of events needs to be considered when analysing data to measure the economic impact of SDS. The number of sectors impacted by SDS throughout a year will depend on the major economic sectors in each country, where and when SDS events occur, and the geography and location of major infrastructure throughout a country. For example, a landlocked country will not have a port sector, thus, sea transportation will not be affected. Also, many countries that have major industries – such as oil and gas exploration and extraction or electronics manufacturing – could face significant costs of SDS if these industries have to cease production due to SDS events.

6.13.2. Types of data required for each sector

Agriculture

Annual crops – Crop losses due to sand or wind blasting can be a complete loss of crops in a particular region or a reduction in yield due to partial losses. To measure these types of impacts, ascertaining areas of all crops – or the most significant crops – in a region or country is necessary. Also necessary is a method to compare yield losses in the cases where yield was affected.

Perennial crops – Similar to annual crops, but there may also be a longer-run effect on some perennial crops if trees or plants, such as Lucerne/alfalfa crowns, are damaged.

Animal production – This can be affected in several ways. If the system is using animals for milk production, there may be a reduction in milk produced during the SDS event, thus costing the producer income with no compensatory reduction in costs.

The SDS event may lead to the loss, either through death or animals fleeing the SDS and the producer not being able to locate them afterwards, so there may be a loss in terms of a reduced number of animals. The final loss for animal producers would be through lost, destroyed or damaged feed stocks, either pasture or forage crops. Measuring these types of variables will be difficult, but if we can capture animal losses, that will at least be a start.

Transport

The transport sector is one of the economic sectors most affected by an SDS event and depending on the transport infrastructure in a country, the costs can be substantial.

Air – The airline industry is most affected due to airport closures leading to cancellation, delay or diversion of aircrafts. This translates into costs for airlines and passengers. The minimum data needed for this are the number of aircrafts delayed, diverted or cancelled at each location. These may be sourced from the national department that handles air traffic or from the airlines themselves. If possible, the number of passengers affected would be really useful, and if possible – but highly unlikely – the costs incurred by the airlines due to the SDS event(s). Also, if possible, the costs of cleaning airport facilities, especially runways and taxiways, would be useful data. One good source of data for estimating the cost of aircraft delay is Cook and Tanner (2011). This research is focused on air traffic control delays but contains numerous estimations of costs for aircraft delay and for passenger and crew costs.

Sea/water – The impacts and costs in this sector will be due to different factors, depending on the aspect considered. For port operations, such as loading and unloading of ships, there could be delays caused by the SDS event(s), and in this case it will be necessary to know, if possible, what the costs of delayed loading/unloading are. For ferry operations, it is necessary to know the number of ferries delayed or cancelled and the number of travellers affected. If possible, finding out how travellers pay for their ferry fare would be useful.

Land – The costs incurred in the land transport sector are due to three separate impacts: road closures, road cleaning and road accidents. Road closures and traffic reduction data may be sourced from the department responsible for road or transport. The impact of closures and similar impacts will usually be relatively small unless a major highway is closed for a significant amount of time.

Road cleaning costs will depend on whether this is undertaken and where road closures are the source of data, the case may be the same.

Traffic accident data are necessary to estimate the costs of injury or death due to accidents. However, it is important to make sure that the accidents occurred during a period of SDS or as a result of low visibility caused by SDS. The source of data for traffic accidents may be the emergency services that attend accidents, or a transport-related agency that collects data on these types of events.

Another cost incurred by the transport sector is reduced income due to loss of business on the day(s) of an SDS event. Some measure of reduced income or number of loads carried would be useful. Again, this may come from a government agency, or even a private transport agency that represents the transport industry, as they may collect data on this.

Infrastructure

Infrastructural impacts of SDS are usually on the physical aspects of the infrastructure, either damage or cleaning of infrastructure. Sometimes, there is no damage or cleaning, depending on the severity of the SDS event. Also, some types of damage cannot be measured and therefore cannot be costed. This is particularly the case with siltation of waterways or dams.

Electricity – The main costs here are damage to pylons or transmission lines, and the main consideration here is that the damage is due to SDS. In some cases, SDS may lead to damage, but there may already be pre-existing conditions that contributed to the final damage caused by SDS. Cleaning of transmission lines and/or insulators may also be undertaken to reduce the potential for electrical short circuits and fires. The costs of damage and/or cleaning could/should be available from the electrical transmission company. Also, in some countries or regions where electricity is generated by solar plants, the costs of cleaning of solar panels may be available from the plants or electricity generation company.

Water and gas

These utilities are not usually affected by SDS, as they are typically underground. However, if there are reports of damage, please gather any data you can.

Construction

The construction industry costs are due to delays in construction. Thus, we need to know how much construction activity is going on in an economy, and how the SDS event(s) impact construction activity, such as how many worksites were closed down and for how long.

Oil and mineral exploration and production

Similar to the construction industry, costs are due to delays in exploration. Therefore, we need to know how much exploration activity is going on in an economy, and how the SDS event(s) impact on exploration activity, such as how many worksites were closed down and for how long. A second impact on the oil and mineral extraction industries is reduced revenue when oil wells or mines are not operating. Therefore, we need to identify if these facilities are impacted by SDS. Some mines, such as underground mines, may be less affected than others, such as open-pit mines.

Commercial activity – Retail/wholesale

Commercial activity is probably the hardest sector to measure, as there are no observable impacts other than the possibility of fewer people purchasing goods. The best way to measure this is through survey data, but in most cases, this is not feasible. To measure the impact, we use a scale of sales activity based on national retail/wholesale sales data, which should be obtainable from one of the economic agencies within a country, such as the central bank or a department of treasury or finance.

Manufacturing

Manufacturing will only be impacted by SDS if the particulate matter enters the manufacturing facility, or if materials required for production are held up in transit, causing delays. For example, electronics component manufacturers in Korea noted that on days of high particulate matter, there were more faulty products or faults in final components. Collecting data on this will be difficult due to facility-specific issues, but may be possible through survey work at a later date, as shown by Kim (2009).

Emergency services

Calls and requests for emergency services, such as police, ambulance or fire, may increase during SDS due to health incidents, fire or road accidents that may be a result of the events. Data for this type of service can come directly from the police, fire or ambulance services, or indirectly through the agency that manages these services. To ensure that there is indeed an increase in service requirements, it is necessary to gather data from comparable periods with no SDS activity.

Health

The impacts on health can usually be measured in either admissions through accident and emergency rooms or some other proxy such as ambulance activity. The best source is through the health department or the agency that manages hospitals in the region impacted by the SDS. Again, it is necessary to have a comparative set of data for periods when there is no SDS activity.

Absenteeism

Absenteeism is the absence from work of employees due to family or caring responsibilities. Some costs of absenteeism are already captured in costs of production, but research has shown that there is a reduction in productivity as well as production. The problem with measuring absenteeism is putting a number on the percentage of people absent from work due to an SDS event, as well as ascertaining the typical absentee rate for a particular country or region with which to compare it.

Households

Many household costs are captured under other headings, such as absenteeism or health, but the major cost for households due to an SDS event is cleaning, which includes cars, internal and external cleaning, and repairs and maintenance of vehicles and structures if necessary. It may be possible to assign some value to these costs if, for example, we know the replacement rate for air conditioners and other types of filters, the duration of the SDS event and how much matter was deposited.

The other costs households incur are for dust mitigation. These can include investments in new doors and windows that seal out dust more effectively, or air-filtration or conditioning systems, so some measure of these would be helpful. However, identifying which investments were made for dust mitigation as opposed to lifestyle improvement may be problematic.

Arts, sports and leisure

Many events and activities in the arts, sports and leisure sector can be limited or cancelled due to health concerns or lack of attendees. Therefore, if it is possible to identify which events may be cancelled and the potential loss of income for this sector, many events that are cancelled are not replaced and ticket holders usually get their money back, again the loss in income is due to the costs incurred in organization and preparation.

Schools and education facilities

School and other education facilities may be closed due to an SDS event, but in many cases, there is no direct loss in income or increased costs, as teachers and other workers in this sector are paid regardless. The main cost in this sector would be parents and carers having to stay at home to care for children and other dependents, and these costs would be captured in the absenteeism chapter.

Concluding comments

In some cases, it may not be possible to directly obtain the data required, but other sources such as media reports, insurance companies or other similar agencies, as well as secondary data, can be used to validate and/or verify estimated or assumed values. In other cases, the sector is not a major sector in the region or country's economy, so it is not critical that the data be collected.


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6.14 Conclusions

This chapter covered an assessment framework for the economic impact of SDS. Different approaches have been discussed and the data requirements for these approaches presented. Types of costs, direct and indirect, market and non-market, and on-site and off-site, were defined. One key point here is the difference between value and cost, which is critical in estimating the economic impact of SDS. SDS impact many sectors of an economy. These sectors were identified and the types of impacts SDS may have on these sectors were discussed.

The challenge with any economic analysis, particularly for natural disasters, is that of data requirements and availability, and this will drive the "ideal" method of analysis. Input-output (I-O) modelling is difficult in the context of SDS, as I-O requires a base-year without SDS as the comparison year for measuring impact. Computable general equilibrium (CGE) models have been used to measure the impacts of natural disasters, but require significant amounts of data, and are reliant on parameters to measure economic impact. Surveys and accounting methods have also been used and do capture the impacts of SDS but require full identification of impacts and assumptions regarding costs and measurement of these costs.

The key aspect of the successful construction of an SDS economic impact assessment is the availability of good data, meaning data that accurately measures the impact of SDS events. Data-collection also needs to be comprehensive to cover all affected sectors of the economy.

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7. A geographic information system-based sand and dust storm vulnerability mapping framework

Chapter overview

This chapter provides a sand and dust storms (SDS)-focused process to assess vulnerability using geographic information system (GIS) procedures where data availability or quality is not a critical issue. The chapter provides a flow chart for GIS-based vulnerability assessment and conceptual models of how SDS affect the health, socio-economic, environmental and agro-ecological domains of a vulnerable area (from local to global). Detailed attention is paid to the selection of vulnerability indicators (including tables of possible indicators). The chapter includes specific formula to produce vulnerability maps using a GIS platform.

This chapter should be read in conjunction with chapters 3, 4, 5 and 6.

7.1 Overview

This chapter describes a procedure for a geographic information system (GIS)-based mapping of vulnerability to sand and dust storms (SDS). The goal is to elaborate this procedure in detail and strengthen the users' ability in understanding practical considerations on data-collection and analysis using a GIS for SDS vulnerability mapping.

As noted elsewhere, data availability and access differ among countries and stakeholders of SDS. The proposed procedure is intended to be applicable and adaptable in different circumstances. This assures that even with limited data accessibility, a basic map of SDS vulnerability can be achieved.

Vulnerability, its components and the relevant indicators exhibit such a large and complex spatial-temporal variability that an interactive GIS-based platform is required to handle them. Accordingly, stakeholders having uneven profiles of data, skills and abilities will be able to adapt this mapping procedure.

This adaptation is closely linked to the level of integration of relevant data, such as GIS layers, remote sensing data, available web data and non-GIS information, into the procedure. To do so, limitations and shortcomings of implementing GIS for sand and dust storm vulnerability mapping (SDS-VM) should be well understood. These limitations include a lack of data, available data not being in GIS format and GIS data having no uniform data model and structure, among other scenarios.

Mapping SDS vulnerability can be subjective if the experiences and opinions of experts and stakeholders are inserted into the procedure (for example, by selecting different sets of indicators) and can create different vulnerability maps for the same SDS phenomenon. It is therefore necessary to propose a general procedure that can provide objective estimates of vulnerability, unbiased towards different users or environmental conditions. The stepwise procedure and the order of specific steps required to implement the procedure are illustrated in **Figure 17**.

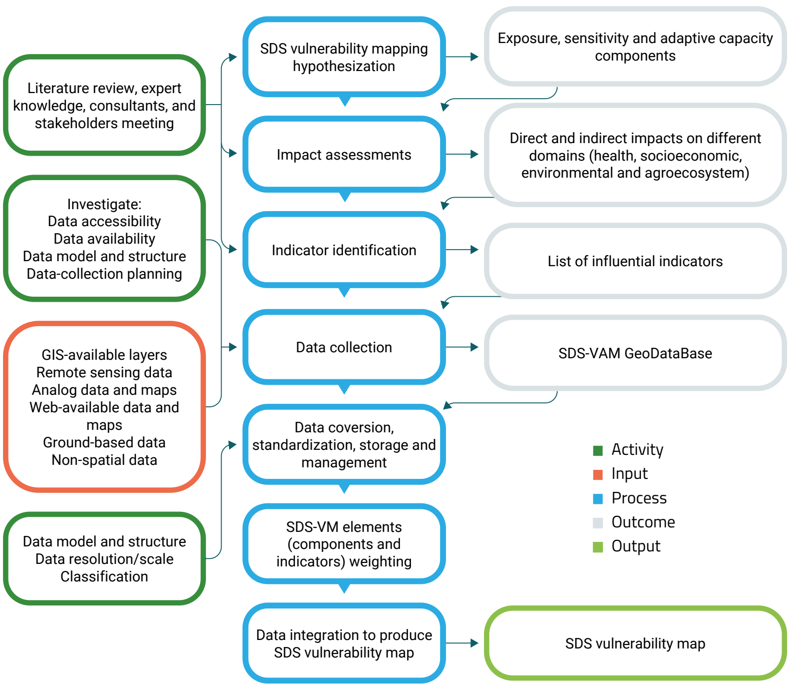


Figure 17. A flowchart of geographic information system vulnerability mapping

7.2 Approaches to an SDS vulnerability mapping and assessment framework

The complex and multidimensional nature of vulnerability makes any mapping methodology framework arbitrary, overlapping and contentious to a degree, depending on disciplinary differences in how to formulate vulnerability (Intergovernmental Panel on Climate Change [IPCC], 2012a). The majority of vulnerability assessments and mapping developed over the past decades involve statistical analysis, designing vulnerability indices and the use of GIS (United Nations Environment Programme [UNEP], 2003).

The empirical-statistical approach is based on the statistical analyses of observed damage data and distributions from past hazard events. Statistical data and techniques (for example, regression, correlation, normalization and statistical indices) are commonly used to identify vulnerable communities and develop composite indices. Such indices combine several particular indicators and deliver simple and usable results from a vast amount of diverse information.

The indicator-based approach estimates the overall vulnerability from a set of indicators representing interactions between hazard and system elements. Indicator-based vulnerability is flexible and applicable to different hazards and it can be easily adapted to user needs (Kappes et al., 2012). However, there is a need to base indicators on evidence or proven models, otherwise they should be used cautiously as a tool for decision-making. Most vulnerability assessment and mapping indicators are model driven and not data driven, making them susceptible to a degree of uncertainty.

Composite indices make the information easily usable by potential users, including governments and public sectors. For instance, the Committee for Development Policy (2000) and the Caribbean Group for Cooperation in Economic Development and the World Bank (2002) used statistically normalized variables with equal weights to construct composite vulnerability indices. However, despite their simplicity and directness, composite indices are prone to delivering poor outcomes in the absence of evidence or evidence-based models. While commonly used, composite indices are often flawed by linking and combining different indicators into one resulting value.

On the other hand, GIS offers a flexible and useful tool to show the spatial distribution of vulnerable regions and communities. By relying on analytical frameworks and proven models, such an approach leads to accurate results. GIS can accept data derived from a variety of sources such as satellite imagery, aerial photography and spatially referenced maps and associated tabular attribute data. This is critical, since data might be collected in different ways and integrated in different forms.

Furthermore, GIS provides a powerful platform for geostatistical/geospatial analysis, as well as visualization and mapping tools. Examples of GIS-based vulnerability mapping are the:

- Climate Change Vulnerability Map, an interactive online GIS platform (http://maps.massgis.state.ma.us/map_ol/cc_vuln.php) provided by the Massachusetts Department of Public Health, Bureau of Environmental Health
- Interactive map of Central America presenting vulnerability to different natural hazards prepared by UNEP/GRID Sioux Falls (1999)
- Food Insecurity and Vulnerability Information and Mapping Systems (FIVIMS), developed by Food and Agriculture Organization (FAO) (1998)

7.3 Key concept of vulnerability assessment and mapping

7.3.1. Vulnerability

The word "vulnerability" has different applications and interpretations in different disciplines. "Vulnerability" may refer to "biophysical vulnerability" that is closely aligned with the concepts of "hazard", "exposure" or "risk", or it may highlight the socioeconomic and cultural processes that are more in line with the concepts of "resilience", "coping capacity", and/or "adaptive capacity" (Preston and Stafford-Smith, 2009). There might also be integrated conceptualization of vulnerability, considering both biophysical and socioeconomic factors that collectively create the potential for harm. Considering only components of biophysical vulnerability (that is, only exposure and sensitivity), regardless of adaptive capacity, can lead to biased estimates of vulnerability and, consequently, an erroneous policy implication (Piya et al., 2016).

Given the multidimensional and complex nature of SDS, it is necessary to consider vulnerability as a function of three interactive components: (i) exposure to change; (ii) associated sensitivities and (iii) related adaptive capacities (Polsky et al., 2007). The first two components directly influence vulnerability so that the more the exposure or sensitivity, the greater the vulnerability.

On the other hand, adaptive capacity is inversely related to vulnerability, thus, an increase in the adaptive capacity will result in lower vulnerability. Multiple definitions exist for the components in different disciplines and the distinctions between them are not always clear. All components, however, are site- and system-specific and vary over time. The three components of vulnerability are explained in the next sections.

7.3.2. Exposure

"Exposure" refers to the nature and degree to which elements of a system are at risk of a natural or human-induced hazard (IPCC, 2012b). Elements at risk could include individuals, livelihoods, ecosystems and resources, infrastructure, environmental, agricultural, economic, and social assets (IPCC, 2014b). Gender, age and health status should also be considered in establishing exposure. Exposure can be considered geographically by identifying the location, characteristics, number and type of elements exposed to hazard or harm. Although sometimes used interchangeably in the literature, there is a distinct difference between vulnerability and exposure.

Exposure can be regarded as a necessary, but not sufficient, determinant of vulnerability (IPCC, 2014a). This means that there might be elements exposed to hazards but that are not vulnerable, while to be vulnerable, it is necessary to be exposed to hazard. Information on exposure is of vital importance for vulnerability assessment to address how at-risk elements of a given system act when subjected to hazard. In the case of SDS, frequency, intensity and duration of exposure to the events are also critical, as they will increase the likelihood of risk for the given elements.

7.3.3. Sensitivity

Sensitivity is another concept related to vulnerability, defined as the degree to which a system is modified or affected by hazard stimuli (IPCC, 2014a). Depending on their characteristics, various systems react differently to the same hazard event. For example, a system might be vulnerable to flood, but not to drought. Sensitivity determines how different elements in a given system respond when hazard events occur.

For a given system, sensitivity can either be limited to identifying whether the system is sensitive to a hazard/perturbation or, in a more comprehensive way, to measure the degree of sensitivity. Sensitivity can also be used to rank different elements of the system based on their sensitivity to hazard/perturbation. Exposure and sensitivity are closely connected determinants of the vulnerability of a system and dependent on the interaction between the characteristics of the system and the attributes of the hazard stimulus (Cutter et al., 2009).

7.3.4. Adaptive capacity

While exposure and sensitivity determine the scale and nature of likely impacts caused by hazards/perturbations, the adaptive capacity of the system quantifies its ability to cope with, manage, recover, and adapt to the potential adverse impacts (IPCC, 2014a). Adaptive capacity, in general, can be expressed as the process, action or state in a system (individual, community, sector and country) to better cope with, recover and adjust to changing conditions and risks.

In the context of SDS, adaptive capacity of a system is seen as adjustments in ecological and socioeconomic behaviours in response to potential or actual SDS events to reduce society's vulnerability. Due to the variability in SDS impacts and consequences, adaptive capacity tends to be context-specific, meaning that it varies from situation to situation, among societies and individuals presenting temporal and spatial variation. Gender, age and health status need to be considered in defining adaptive capacity.

7.4 Impact indicators of SDS for vulnerability mapping

7.4.1. Measuring vulnerability

Vulnerability is not an intrinsic property of a system to be directly observed or measured. Instead, it has to be deduced through a set of variables (indicators) estimating exposure, sensitivity and adaptive capacity. A common practice to estimate vulnerability is to use surrogate measures of vulnerability components and then aggregate them to yield the overall vulnerability "score".

Different vulnerability assessments can be classified based on the vulnerability factors that they consider (Füssel, 2007). Human and natural systems are fundamentally interlinked and risks to one would eventually translate into risks to the other (UNEP, 2003).

This means that the measure of vulnerability should include factors from both humans and the environment, plus the associated risks to both.

The United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN/ISDR) (2005), for instance, classified four groups of vulnerability factors associated with hazard reduction: physical, economic, social and environmental. Vulnerability factors, in turn, can be inferred from the impacts of hazard on different aspects of system. Accordingly, in this document, the impacts of SDS are grouped into four main domains including human health, socio-economy, environment and agroecosystem.

Each domain has a number of subdivisions, which map out the major elements of interest. These impacts are then used to select the ultimate set of indicators to assess SDS vulnerability and produce maps. The mapping process also needs to discern how vulnerability may differ by the gender, age or health status of the individuals being assessed.

7.4.2. Human health

SDS threatens human health and safety in many ways, by affecting the environment that provides us with clean air, food, water and security (Goudie, 2014). Assuming that the impacts of SDS are projected to increase over the coming decades, current health threats will likely persist and intensify. The health impacts of SDS are dependent on:

- the location of human populations with respect to the emission sources of SDS and the downwind direction of dust transport and deposition
- the amount of suspended materials that SDS contain
- particle sizes and chemical compositions (ibid.) and the health status of the vulnerable population

There are generally three types of health impacts:

- **Type 1.** Medical and physical health
- **Type 2.** Mental health and well-being
- **Type 3.** Community health

Type 1 considers human health impacts of air pollution and contamination pathways caused by SDS. Depending on their origins and pathways, SDS may transport heavy metal, residue of chemicals including plant fertilizer, pesticides and herbicides, dioxins, toxic hydrocarbons, radionuclide contaminants and radioactive isotopes (ibid.).

The fine dust particles, bacteria, pollen and fungi carried by dust storms are reported to have important effects on human health (Péwé, 1981). Suspended materials in the air can be inhaled and cause serious disorders if they accumulate in the respiratory system. Although reporting inconsistent results across different studies and geographical locations, the literature includes several studies reporting health impacts associated with SDS (e.g. Nativ et al.,1997; Choi et al., 2011; Tam et al., 2012; Baddock et al., 2013; Martinelli, Olivieri and Girelli, 2013; Deroubaix et al., 2013; Sprigg, 2016; Middleton, 2017). Among them, four reviews (de Longueville et al., 2013; Hashizume et al., 2010; Karanasiou et al., 2012; Zhang et al., 2016) have noted similar results, suggesting that potential health effects associated with SDS may increase cardiovascular mortality and respiratory hospital admissions.

Type 2 refers to mental health and well-being effects of SDS that may cause stress, anxiety, depression, grief, sense of loss, strains on social relationship and post-traumatic stress disorder. These kinds of effects are integral parts of the overall SDS-related human health impacts. Although these effects may rarely occur in isolation, they often interact with other socioeconomic and environmental stressors.

Type 3 considers the overall SDS-related impacts on the health of groups and communities. The community health effects can lead to increased interpersonal aggression, increased social instability and decreased community cohesion. The main pathways and types of health impact of SDS are shown in **Figure 18**.

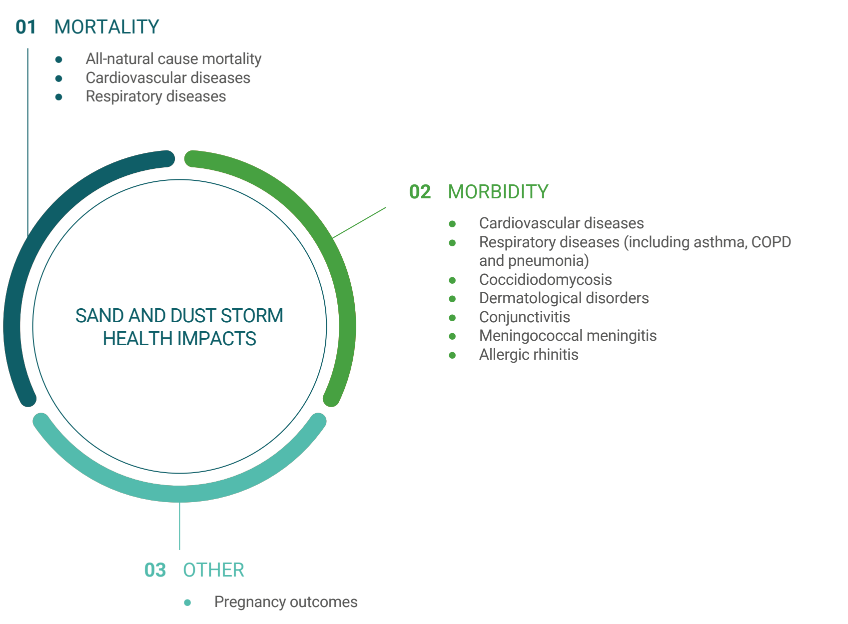


Figure 18. Major human health impacts of sand and dust storms

The direct impacts on health are mostly caused by changes in exposure to SDS. Communities and individuals differ in their vulnerability to certain health outcomes. A community's health vulnerability is a function of health outcome sensitivity and its capacity to adapt to new conditions. Several factors such as environmental conditions, population size, growth, age, sex, density, food availability, education level, income level, pre-existing health status and the availability and quality of public health care affect a community's health vulnerability.

It is likely that poor populations, and particularly older persons, due to their lower immunological capacity and the very young, due to their not fully developed lungs and airways, are at greatest health risk to SDS. The vulnerability of the poor may endanger the well-being of other members of the same community and hence increase the overall vulnerability of the population.

7.4.3. Socioeconomic domain

SDS have profound impacts on socioeconomic systems of different scales, from local up to the global economy. The immediate impacts can be remarkable. China's economic losses due to dust storms and desertification is estimated to amount to US$ 6.5 billion per year (Youlin, Squires and Qi, 2002).

Nonetheless, it is believed that the actual socioeconomic impacts of SDS are difficult to measure because of the long-term consequences and implications they have on the society and economy (United Nations Convention to Combat Desertification [UNCCD], 2016). SDS socioeconomic impacts are more severe as the storms cross populated areas and industrial zones such as big cities and towns. They cause significant harm, both at their sources and through their deposition in downwind areas by reducing air quality and depositing particles (Chan et al., 2005). These impacts encompass a relatively broad range of effects across many sectors of the economy and society.

In general, socioeconomic costs will likely escalate as a result of dust storms (Jeong, 2008; Meibodi et al, 2015). For example, the loss of topsoil, resulting in the loss of soil nutrients, carbon and organic matter, is among on-site costly damages of SDS (Leys, 2002). Sand and dust deposition can harm vegetation by covering them and reducing the photosynthesis process through blocking sunlight or even burying vegetation cover in some areas. Infrastructure can also be sandblasted or buried by SDS. Deposited dust increases cleaning costs, such as for telegraph poles, fencing, walls, railway sleepers and roads (Middleton, 1986; 2017), buildings and streets (Huszar and Piper, 1986). As an example, Huszar and Piper (ibid.) summarized that the major off-site impact of dust storms in the USA was on households, mainly because of cleaning costs of interior spaces and domestic landscapes.

SDS can also cause major damages to utility systems such as power distribution grids (Maliszewski, Larson and Perrings, 2012), solar power plants (Sarver, Al-Qaraghuli and Kazmerski, 2013), radio/microwave satellite and ground communications (Abuhdima and Saleh, 2010) and rail networks (Cheng et al., 2015).

Human activities can be limited, including closure of transport networks and road traffic during SDS (Deetz et al., 2016; Goudie and Middleton, 2006), air trafficking problems (Holyoak, Aitken and Elcock, 2011), flight cancellations and delays (Kang, 2004), and other air transport effects (Tozer and Leys, 2013). SDS can also impose considerable costs on individuals and business owners in both urban and rural areas (Anderson, van Klinken and Shepherd, 2008).

Continued SDS over several years would cause forced migration by destruction of farmlands and facilities (Gregory, 1991). For example, hundreds of thousands of people were forced to leave their homes and migrate because of the Dust Bowl in the 1930s (Hurt, 1981).

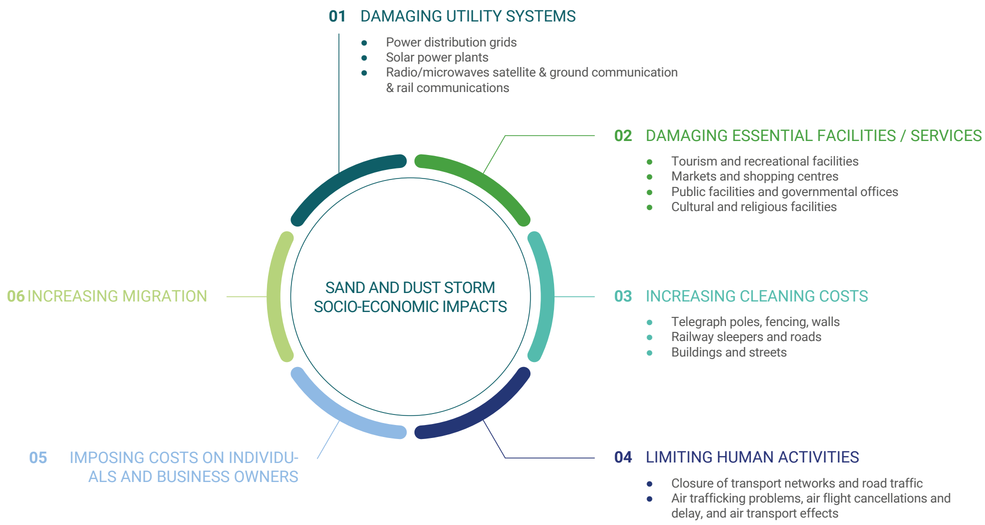


Figure 19. Major socioeconomic impacts of sand and dust storms

Tourism and recreational facilities, markets and shopping centres, public facilities and governmental offices, cultural and religious facilities can also be drastically affected by SDS events. Water resources back-up facilities such as dams, reservoirs, catchments and flood-control installations may be filled up with sand. **Figure 19** depicts the major socioeconomic impact of SDS.

7.4.4. Environment domain

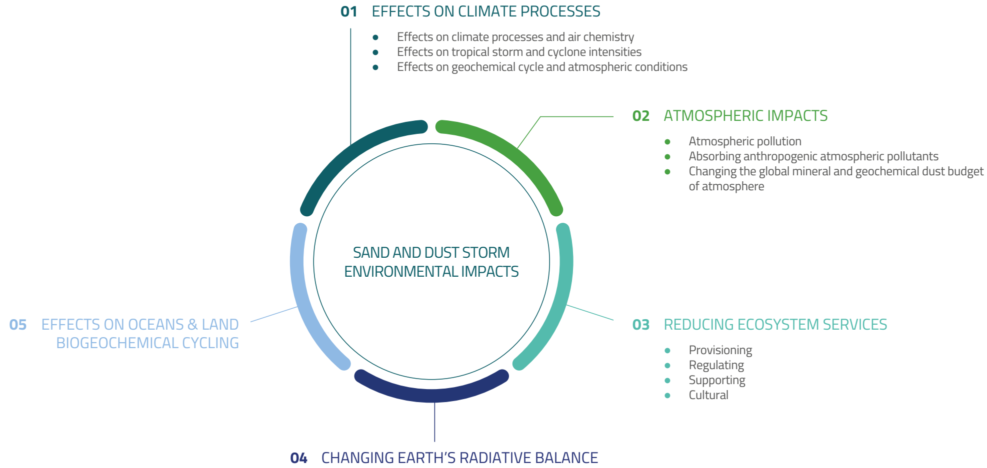
There is significant concern about the impacts of SDS on the environment. SDS have most of their impact within the atmosphere and significantly contribute to atmospheric aerosol loads and pollution (Xie et al., 2005; Xin et al., 2007; Zakey et al., 2006).

The reduction of planetary insolation caused by suspended particles in the atmosphere can have a cooling influence on climate (Seinfeld et al., 2004) and alter Earth's radiative balance (Highwood and Ryder, 2014). This cooling influence, along with varying aerosol loads in the atmosphere, change the atmospheric dynamic structure and modify the atmospheric circulation pattern, with implications for climate change (Shao et al., 2007; Won et al., 2004).

SDS events can impose direct effects on climate processes and air chemistry (Kim et al., 2003), atmospheric geochemical cycles (Shao et al., 2011) and influence oceans and land biogeochemical cycling (Gabric et al., 2010). Dust storms can also have important impacts on tropical storm and cyclone intensities (Evan et al., 2006). SDS transport huge quantities of mineral dust particles from deserts and farmlands and therefore affect the global mineral and geochemical dust budget of atmosphere (Knippertz, 2014; Zender et al., 2004). Moreover, dust particles in the atmosphere can absorb other anthropogenic atmospheric pollutants (Onishi et al., 2012) and transport them to other areas.

Another major impact of SDS on the environment is the reduction of ecosystem services (Lal, 2014) including the four categories: provisioning, regulating, supporting and cultural services. Ecosystem services are contributions of ecosystems to both directly and indirectly support human survival and well-being. Negative impacts on these systems influence the quality of human life. The main environmental impacts of SDS are shown in **Figure 20**.

Figure 20. Major environmental impacts of sand and dust storms



7.4.5. Agroecosystem domain

SDS can have several negative impacts on agroecosystems through soil erodibility, sediment deposition and photosynthesis reduction on agricultural lands (Sivakumar, 2005; Stefanski and Sivakumar, 2009). The worst impact of SDS on agroecosystems is the stripping of topsoil from farmlands that accelerates soil erosion and land degradation and lessens soil productivity (Zobeck, Fryrear and Pettit, 1989).

Topsoil is the most fertile fraction of the soil, made up of minerals and decomposed organic matter that can be removed and transported over long distances. In the long term, SDS can change the nature of soils (Menéndez et al., 2007), as well as their chemical, physical and biological characteristics (Huszar and Piper, 1986). They can also impact contribution of micronutrients to ecosystems (Boy and Wilcke, 2008), cause soil loss (Riksen and De Graaff, 2001) and reduce its water-holding capacity.

A further significant impact of SDS on agroecosystems is through either direct or indirect loss of crop yield and livestock. Direct impacts include physical damage to crops, animals and trees caused by SDS.

Crop yield reduction can be triggered by carrying seeds (Larney et al., 1998), total or partial burial of seedlings under sand and dust deposits, loss of plant leaves as a result of sandblasting and delaying plant development.

Plants exposed to sandblasting (or buried under sand and dust deposits) may lose their leaves, resulting in reduced photosynthetic activity (Sharifi, Gibson and Rundel, 1997) and consequently reduced plant dry matter production that is necessary for plant growth and the development of grain or fruit (Stefanski and Sivakumar, 2009). Direct impacts can be considered in terms of short-term, temporary damage at a particular crop stage (for example, early season, maturity or before harvest) during the growth season to complete crop loss.

SDS may also change the physical and chemical characteristics of a plant's leaves (Farmer, 1993) and reduce plant's biomass (Burkhardt, 2010). Livestock not properly sheltered during the storms could suffer directly (Mu et al., 2013).

For instance, during two dust storms that occurred in China in May 1993 and April 1998, 120,000 and 110,000 livestock were killed, respectively (Shao and Dong, 2006). Environmental stresses caused by SDS can also reduce livestock productivity and growth (Starr, 1988).

SDS can also cause indirect damages such as loss of potential production due to disturbed access to goods and services and increased costs of production. These indirect impacts are the expected result of low incomes, production decline, environmental degradation and other associated factors (Das et al., 2003).

Besides, SDS can increase disease risk of organisms, such as trees, crop plants and animals (Kellogg and Griffin, 2006), threatening food production by affecting rangeland and agricultural productivity (Issanova et al., 2015). They can intensify drought (Han et al., 2008) and even change precipitation regimes (Knippertz and Stuut, 2014) and such changes could eventually negatively affect agroecosystems. The major impact of SDS on agroecosystems are shown in **Figure 21**.

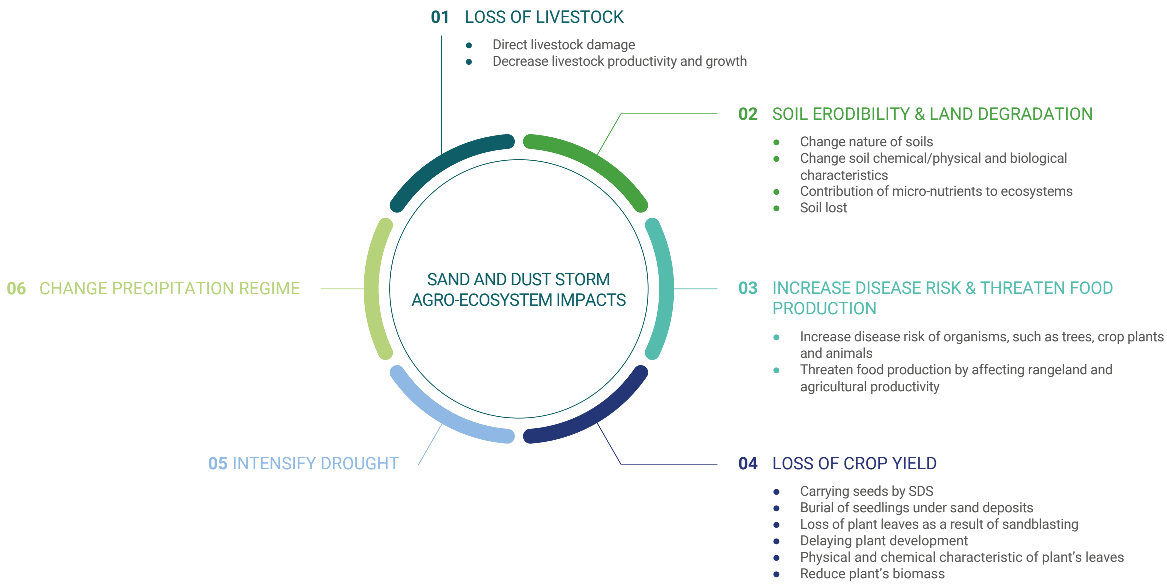


Figure 21. Major impacts of sand and dust storms on agroecosystems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7.5 Identifying indicators for SDS vulnerability mapping

In order to include an indicator in the analysis of SDS-VM, the following questions should be considered:

Question 1: How do the given indicators (GIS data layer) contribute to vulnerability to SDS?

Question 2: To which vulnerability component(s) (exposure, sensitivity or adaptive capacity) does the given indicator belong?

Question 3: To which level of analysis (local, sectoral, national or international) does the given indicator belong?

Answers to these questions will determine whether a particular indicator should be included in the analysis.

Annex 1 includes the answers to these three questions for each indicator. The potential source of data collection for each indicator is also provided. Alternative web-based data (the majority of which are freely available) are also provided in the tables. Detailed descriptions and web addresses of these sources are given in **Annex 2**.

Where no appropriate data are available, (indicated with "NA"), guidance on how to measure, calculate or extract the given indicator is outlined. Data provided by these sources often vary in scale, quality and content. Therefore, different users must decide which data among all the given sources best suits their needs. The data format of each indicator has also been provided in **Tables 9 to 17** (indicated with "DF" in the tables). However, in some cases, data might be provided in different formats that require conversion.

In summary, the list of the main indicators is provided based on expert assessment and literature review, including all necessary information on data acquisition, data necessity and data sources for SDS-VM. It is then up to the end users at different levels (residential, ecosystem and political levels) to decide how the associated indicators should be valued and weighted, and how vulnerability should be acted upon.

An ideal SDS-VM would require precise measurements of all the impacts of SDS as input indicators to estimate the vulnerability. However, in practice, several impacts are either not measurable or very difficult to measure. Besides, all the impacts are not equally important; some are only influential under particular circumstances. It is therefore reasonable to restrict them to a set of quantifiable (measurable) indicators.

The relevant indicators for mapping SDS vulnerability are listed in **Tables 9 to 17** (**Annex 1)**. Attempts are made to include a large number of indicators associated with SDS vulnerability components, but availability and accessibility of data pose practical limitations on the number finally included in the methodology. These indicators are selected based on the existing literature, experts' knowledge and their contribution to different components of SDS-VM.

The inclusion of some indicators into different components is relatively subjective. Indicators determining the extent and intensity of SDS are assigned to the exposure component. Those indicators reflecting the system's susceptibility to perturbation are included in the sensitivity component. Indicators that are rather more responsive to policy development and prevention strategies are considered as adaptive capacity.

Nevertheless, there are indicators that might be shared among different components. To summarize, this chapter provides an expert assessment of key impacts and indicators to SDS-VM. However, it is then up to the end users at different levels (residential, ecosystem and political) to decide how the associated indicators should be valued and weighted, and how vulnerability should be acted upon.

7.6 A geographic information system-based stepwise procedure for SDS vulnerability mapping

7.6.1. SDS vulnerability mapping hypothesis

SDS vulnerability mapping can be hypothesized based on the relationship between the system's exposure, its sensitivity and the adaptive capacity. Hence, in order to formulate an appropriate mathematical relationship for vulnerability mapping, extensive literature review and expert consultation is specifically required.

The estimation of SDS-VM components requires measurable indicators which are often affected by a number of limiting factors including data availability and applicability, mapping objectives, precision and accuracy of vulnerability maps, the SDS characteristics (for example, spatial-temporal behaviour, chemical and mineralogical compositions, SDS impacts and the different stages of SDS events (emission, transport and deposition)). Therefore, careful considerations of these factors must be provided in the hypothesis.

7.6.2. SDS impact assessment

The SDS vulnerability components have to be measurably expressed in the form of direct and indirect impacts on different scales and in different categories. Therefore, a careful and thorough literature review on impact assessment for directing the SDS vulnerability mapping to measurable indicators is conducted and a wide-ranging and comprehensive methodology for assessing the impacts of SDS is adapted.

Accordingly, four main domains of impacts (human health, socio-economy, environment and agroecosystems) are categorized. These four categories need to be measurably transformable into indicators (for example, GIS layers) for the GIS-SDS-VM. This depends on the level of economic, social or technological developments, as well as some influential parameters such as distance from SDS sources and physical-chemical characteristics of SDS particles. SDS impacts can vary over different areas and levels, requiring critical care in the SDS impact assessment.

7.6.3. Indicator identification

"Indicator identification" describes how to transform assessed impacts of SDS into quantifiable indicators (GIS layers) to which associated variables are categorized. Different stakeholders (users) may choose a set of indicators from those provided in **Annex 1**, depending on their needs, or follow similar criteria and add new indicators to the list.

7.6.4. SDS data collection

There do not appear to be specific protocols for required GIS data types, models and structures for a GIS-based SDS-VM. This document mainly focuses on activities to provide basic data requirements for GIS analysis to target the needs of SDS-VM. Data collection is the most expensive activity of any GIS-based analysis, as well as vulnerability mapping. SDS-related data are very heterogeneous, based on their many diverse sources and the data-capturing processes.

Data collection, including primary (direct measurement) and secondary (derived from other data sources) data, is carried out in different spatial scales and for different purposes in both raster and vector data models. Several different sources to collect data on the relevant indicators are provided and alternative sources are listed in **Tables 9** to **17 (Annex 1)**. The same sources might be used for different indicators and afford the user the freedom to select sources for data collection.

7.6.5. Data conversion, standardization, storage and management

Data always differ according to certain applications and data acquisition techniques. Data models, for example, vector (point, line, area) and raster (pixel, grid), are two different spatial representations with different advantages and disadvantages to be compared with each other for GIS analysis. Other non-spatial data sources also need to be converted into spatial representations and all data must be transformed into the same data model and structure (for example, map projection, spatial scale and data format).

Unification of different measurement scales (such as nominal, ordinal, interval and ratio) of the indicators is a prerequisite step in GIS analysis. Thus, scaling or standardization must be applied to convert the inconsistent data to unique scale and units. There is a number of methods for standardizing for different purposes (Hwang and Yoon, 2012; Massam, 1988). In the GIS-based SDS-VM, the fuzzy membership functions (Jiang and Eastman, 2000) and the score range procedure (Malczewski, 1999; Malczewski and Rinner, 2015) are more adaptable to standardize the available data.

Different techniques for GIS data storage and management are available to organize spatial and tabular data to be retrievable for updating, querying and analysis. There are several geodatabase management systems applicable for the SDS-GIS-VM. As an example, ARCGIS® geodatabases[1] can be used to store and manage data sets in three levels:

1. File geodatabases: stored as folders in a file system, each data set is held as a file that can scale up to 1 TB in size. The file geodatabase is recommended over personal geodatabases.
2. Personal geodatabases: all data sets are stored within a Microsoft Access data file, which is limited to 2 GB.
3. Enterprise geodatabases: also known as multi-user geodatabases, they can be unlimited in size and numbers of users. Stored in a relational database using Oracle®, Microsoft SQL® Server, IBM DB2®, IBM Informix®, or PostgreSQL®.

7.6.6. Weighting of SDS vulnerability mapping elements

Due to the complex nature of the SDS phenomenon and the status of the SDS-VM elements (the components and indicators) with unequal influences, the weighting methodology is a prerequisite for data integration to produce an SDS vulnerability map. Therefore, in order to express the importance of each VM's element relative to others, the weighting functions are required.

A number of methods are developed for weight allocation in different disciplines that are mostly based on ranking from the experts, literature reviews and previous studies (Choo et al., 2012). The GIS-based weightings are mainly carried out in global and local approaches. Global methods assume the spatial homogeneity of measured variables and consequently a single weight will be assigned to each indicator (GIS layer). Ranking, rating and pairwise comparison approaches are common global weighting approaches (Malczewski, 2006).

Unlike global methods, the local approaches allocate weights based on measuring spatial heterogeneity within each indicator (Malczewski and Rinner, 2015). The proximity-adjusted criterion weights, range-based local weighting, and entropy-based local weighting methods are commonly used as local weighting approaches (Malczewski and Rinner, 2015).

1 http://www.esri.com, https://desktop.arcgis.com/en/arcmap/10.3/manage-data/geodatabases/types-of-geodatabases.htm

In any scoring/weighting process, the greater the number allocated to an indicator or component, the more that indicator or component will influence the final vulnerability map of the GIS analysis. Although different weighting methods can be used in SDS-VM, the weighting method of the analytic hierarchy process (AHP), a pairwise comparison method introduced by Saaty (1980), is recommended for GIS-based SDS vulnerability mapping, due to its applicability and simplicity in weight allocation.

7.6.7. Integration of indicators to produce a map of components

Another critical step in SDS-VM, after selecting indicators of exposure, sensitivity and adaptive capacity and their relative weights, is finding out how to integrate these indicators to construct component maps. Once the weight for each indicator (as well as weights of the components) is obtained, the spatial data integration will be carried out through a raster overlay process to produce exposure, sensitivity and adaptive capacity maps. The component maps are created through Equation 7.1.

$$Component\ map = \sum_{i}^{n} indicator * weight$$

(Equation 7.1)

7.6.8. Components map integration to produce SDS vulnerability maps

For the creation of a final vulnerability map, the literature includes three main equations (IPCC, 2012a; UNEP, 2003):

Vulnerability map=Exposure+Sensitivity - Adaptive Capacity

(Equation 7.2)

Vulnerability map=(Exposure*Sensitivity) /Adaptive Capacity

(Equation 7.3)

Vulnerability map= Exposure*Sensitivity - Adaptive Capacity

(Equation 7.4)

These equations show profound differences between the ways that the ultimate vulnerability map can be calculated.
Depending on which equation is used for the calculation, the outcome vulnerability map is expected to be inevitably different. Deciding whether adding, multiplying or dividing the indicators should be selected is therefore a significant issue. A practical solution to test the equations is to run the data for a single location, applying each equation and using knowledge from experts' reviews, the results most closely matched reality. This, however, is not a trivial task and requires both knowledge experts and suitable data sets.

In the context of SDS-VM, different components should not be equally considered, since they do not share a linear relationship, as increasing exposure is not linearly linked with the increase in sensitivity. Thus, Equation 7.2 giving equal weights and importance to all the components is not recommended to calculate SDS-VM. Moreover, expressing the SDS-VM equation as a ratio with adaptive capacity as the denominator (as in Equation 7.3) may bias the output vulnerability for marginal values of adaptive capacity. In this case, very low (or high) adaptive capacity will force the vulnerability to be very high (or low). It is hence recommended to create vulnerability maps using Equation 7.4.

7.7 Conclusion

Many arid and semi-arid areas worldwide are currently experiencing an increase in the occurrence, distribution and severity of SDS that seem likely to intensify in future. Understanding the expected damage or harm resulting from these events, that is, the level of vulnerability of a society exposed to SDS, is vital, to formulate well-targeted adaptation and mitigation policies and strategies.

Vulnerability is a multidimensional and complex concept, generally expressed as "the capacity to be wounded". Vulnerability to SDS, as a multi-cause and multi-faceted phenomenon, is contextual and dynamic and encompasses temporal and spatial considerations. It depends on a variety of factors from different domains including health, socio-economy, environment and agroecosystems.

Any vulnerability mapping will necessarily include some assumptions on its three main components of (1) exposure, (2) sensitivity and (3) adaptive capacity. Assumptions can be made in selecting the appropriate indicators to express the components to the measurement and weighting of a given indicator. These assumptions introduce uncertainty into the calculation of each component and will inevitably be aggregated into the ultimate vulnerability map. The inherent complexity and assumptions make any SDS vulnerability mapping methodology subjective, overlapping and contentious to a degree.

Several approaches are available to quantify vulnerability to different environmental hazards. Statistical tools, composite vulnerability indices and GIS-based mapping are among the most prevalent approaches in the literature. This chapter has presented a conceptual GIS-based framework to produce SDS vulnerability map.

Comprehensive consideration is given to the selection of appropriate indicators to measure three vulnerability components based on a careful study of identifying SDS hazardous impacts on different dimensions of human life and the environment. A broad range of indicators are included according to the existing literature, expert's knowledge and their contribution to different components of SDS vulnerability.

However, data availability and accessibility posed practical limitations to the final number of relevant indicators included. Major indicators are listed in tables where necessary information on data acquisition, potential data sources, alternative web-based data and relevancy for SDS vulnerability are given. Attempts are made to provide a general methodological framework so that it can easily be adapted by different stakeholders according to their necessities and challenges.

In this sense, end users will decide how to incorporate different indicators and how to value and weight them in the calculation of SDS vulnerability. This guarantees that even with limited data availability and accessibility, a basic map of SDS vulnerability is achievable.

Moreover, a stepwise GIS-based procedure including specific steps required to implement SDS vulnerability mapping is provided to avoid ambiguity for the users. These steps involve a hypothesis, impact assessment, identifying indicators, data collection, data standardization, weighting, indicator integration to produce a component map and finally components map integration to produce an SDS vulnerability map. Each step is elaborated in detail and practical considerations on various procedures are discussed.

This document is the first effort in developing a methodology framework to assess and map SDS vulnerability as no such methodology exists in the literature. The aim was to present an integrated methodology framework to provide a picture of society's vulnerability to SDS on local to global scales, enabling planners and policy/decision makers to compare the relative overall human vulnerability due to SDS at different levels. The proposed methodology has to be implemented and evaluated through case studies in different sectors, as well as different countries. Further research is required to study driving forces of SDS, its different impacts, indicator identification and three vulnerability components, as illustrated in **Figures 18, 19, 20** and **21**.

Annex 1: Potential indicators for SDS vulnerability mapping

Table 9. Base data

Category	**Indicator (GIS data layer)**	**Possible source**	**Alternative web-based data**	**Questions (chapter 7.5)**
Base maps	Administrative unit (national, provincial/state, city, town, district and village boundaries) DF: polygon	National map services	DIVA-GIS; Database of Global Administrative Areas (GADM); OpenStreetMap®; Global Land-Use Dataset; Google Maps services; GEONETWORK; Socioeconomic Data and Applications Center (SEDAC) **NA:** Can be extracted from remotely-sensed imageries and web-based map services.	**Q1:** Administrative units serve as the basis and starting point for vulnerability mapping, upon which all the other spatial data are based. **Q2:** – **Q3:** All levels.
	Elevation, slope and aspect DF: point/raster	National topographic services	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM); Shuttle Radar Topography Mission (SRTM); Natural Earth; DIVA-GIS; Consultative Group on International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI); GEONETWORK; SEDAC **NA:** Topographic data can be estimated from satellite (radar, LiDAR and stereo images) data.	**Q1:** Topographic risk is an integral part of most vulnerability mapping, in particular SDS-VAM. **Q2:** Exposure. **Q3:** All levels.
	Land-use/land cover DF: raster/polygon	National map services	DIVA-GIS; SEDAC; OpenStreetMap; Global Land-Use Dataset; GEONETWORK; United States Geological Survey (USGS) Land Cover; Moderate Resolution Imaging Spectroradiometer (MODIS) products; SEDAC **NA:** Vegetation maps (forest and agriculture) can replace this layer if no data are available. Such maps can also be estimated from satellite imageries.	**Q1:** Land cover and/or land-use influence the occurrence, intensity and duration of SDS both at the source and deposition areas. **Q2:** Sensitivity. **Q3:** All levels.

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
	Watersheds DF: polygon	National statistical services, national hydrological organizations	HydroSHEDS; GEONETWORK **NA:** Vegetation maps (forest and agriculture) can replace this layer if no data are available.	**Q1:** Information on watersheds is important for combating sources of SDS and provides a basis for studies on the scale of basins. **Q2:** Sensitivity. **Q3:** Watershed level.

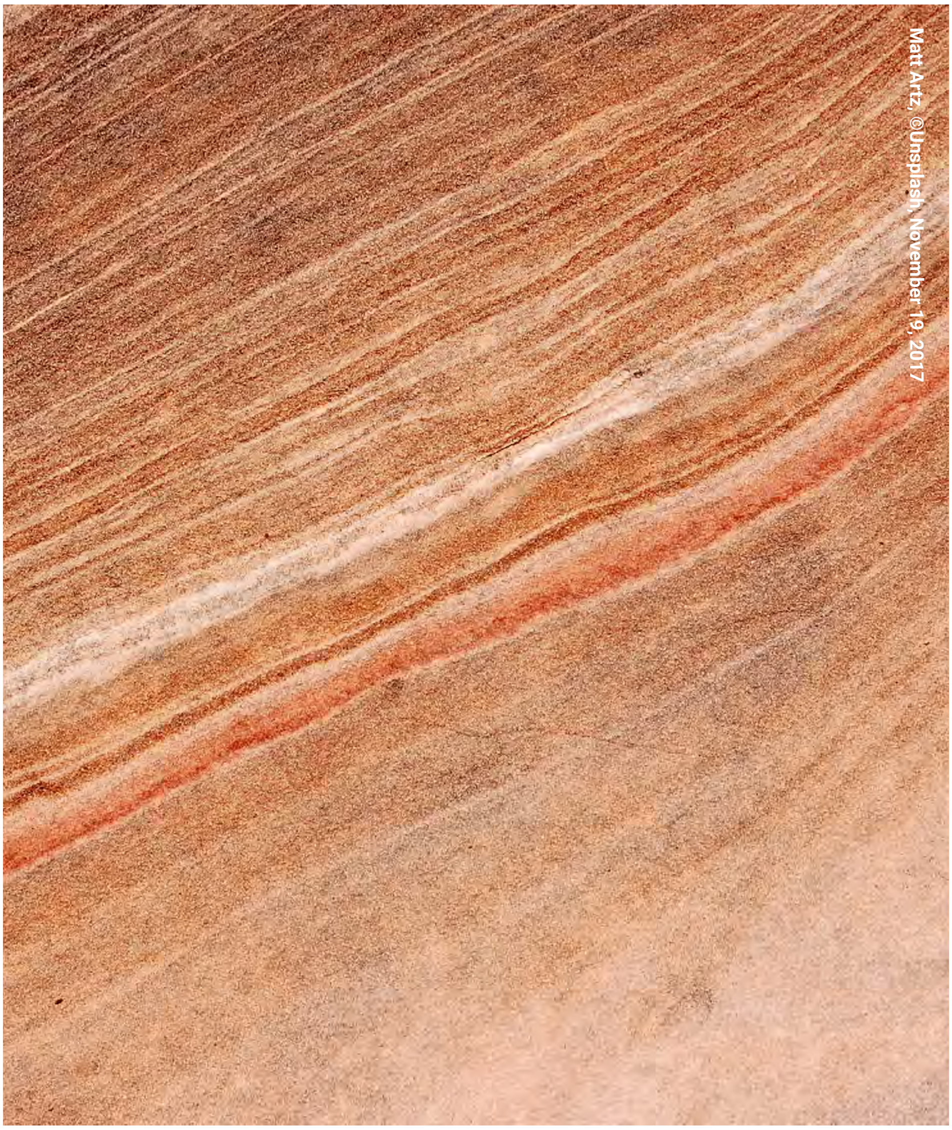

Table 10. Demographic and socioeconomic data

Population distribution map (demographic data)	Age, gender, ethnic groups DF: point/polygon	Census data	World Bank Geodata; SEDAC **NA:** Regional and global estimations can be considered.	**Q1:** Characteristics like age, gender and ethnicity can influence vulnerability. **Q2:** Sensitivity and adaptive capacity. **Q3:** All levels.
	Population density DF: point/polygon	Census data	DIVA-GIS; SEDAC; WorldPop; Global Land-Use Dataset; GEONETWORK; World Bank Geodata **NA:** Regional and global estimates can be considered.	**Q1:** Higher population density and growth cause congestion and dense infrastructure and hence increase vulnerability. **Q2:** Sensitivity. **Q3:** All levels.
	Population growth rate DF: point/polygon	Census data	WorldPop; Atlas of the Biosphere; World Bank Geodata; SEDAC **NA:** Regional and global estimates can be considered.	
Socioeconomic and sociopolitical map	Household wealth and income DF: point	Census data	World Bank Geodata; SEDAC **NA:** Regional and global estimates can be considered.	**Q1:** Socioeconomic and sociopolitical circumstances are among the main drivers of adaptive capacity and influence vulnerability. **Q2:** Sensitivity and adaptive capacity. **Q3:** All levels.
	Infant mortality rate DF: polygon/point	Census data	SEDAC; World Bank Geodata **NA:** Regional and global estimates can be considered.	
	Poverty index DF: polygon/point	Census data	SEDAC; GEONETWORK; World Bank Geodata **NA:** Regional and global estimates can be considered.	
	Education level DF: point/polygon	Census data	OpenStreetMap; GEONETWORK **NA:** Regional and global estimates can be considered.	
	Conflict events/ political violence DF: polygon	National and international reports provided by different organizations	Uppsala Conflict Data Program (UCDP); Armed Conflict Location & Event Data Project (ACLED) **NA:** Regional and global estimates can be considered.	

Table 11. Health and sand and dust storm data

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Health	Health infrastructure index DF: polygon	Census data	GEONETWORK; World Bank Geodata **NA:** Regional and global estimates can be considered.	**Q1:** Health infrastructure index can lower vulnerability by promoting adaptive capacity. **Q2:** Adaptive capacity. **Q3:** All levels.
	Emergency response facilities DF: point	National map services; thematic maps	OpenStreetMap **NA:** Regional and global estimates can be considered.	
	Human health index DF: polygon	Census data	GEONETWORK; World Bank Geodata **NA:** Regional and global estimates can be considered.	**Q1:** Health status is among immediate impacts of SDS and can significantly influence vulnerability. **Q2:** Sensitivity. **Q3:** All levels.
	Livestock DF: point	Agriculture census data	GEONETWORK; SEDAC **NA:** Regional and global estimates can be considered.	
	Wildlife DF: point	Wildlife census data	SEDAC; UN Environment Programme World Conservation Monitoring Centre (UNEP WCMC) **NA:** Regional and global estimates can be considered.	
SDS data	SDS DF: raster	SDS content map; spatial-temporal expansion map; concentration map	MODIS products **NA:** Can be extracted from satellite data (optical and LiDAR data).	**Q1:** SDS-related data are used to map vulnerability through exposure component, as the higher the exposure, the higher the vulnerability. **Q2:** Exposure. **Q3:** All levels.
	Aerosol optical depth (AOD) DF: raster/point	AOD map; ground stations data	MODIS products; AERONET **NA:** Can be calculated using a range of satellite data.	
	Visibility DF: raster/point	Meteorological data; Synoptic weather stations data	Calculated from MODIS products and AERONET **NA:** Can be calculated using AOD data.	
	SDS numerical model outputs (e.g. Weather Research and Forecasting Model (WRF), WRF-Chem and DREAM) DF: raster	Numerical models output data (e.g. World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO-SDS-WAS))	Barcelona Supercomputing Centre **NA:** Regional dust models.	

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Table 12. Meteorological data

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Meteorological and climate data	Precipitation DF: raster/point	Meteorological data (stations)	WorldClim; GEONETWORK; Climate Research Unit (CRU) Climate Datasets; GCM Downscaled Data Portal **NA:** Can be derived from remote sensing satellites (e.g. Tropical Rainfall Measuring Mission (TRMM))	**Q1:** Meteorological factors directly influence SDS formation and spatial-temporal expansion and hence affect vulnerability. **Q2:** Sensitivity. **Q3:** All levels.
	Aridity Index	Aridity map	Global Aridity Index **NA:** Can be extracted based on meteorological data and remote sensing.	
	Natural disaster hotspots (drought and dust storm)	Disaster hotspot map	Natural Disaster Hotspots **NA:** Can be extracted based on meteorological data and remote sensing.	
	Temperature (time series) DF: raster/point	Meteorological data (stations)	SEDAC; GEONETWORK; CRU Climate Datasets; GCM Downscaled Data Portal **NA:** Can be derived from remote sensing satellites (e.g. MODIS).	
	Wind speed and direction DF: polyline	Meteorological data (stations)	CRU Climate Datasets; MODIS products; GCM Downscaled Data Portal; Hysplit model; WMO data portal **NA:** Can be derived from remote sensing satellites (e.g. CALIPSO, CloudSat).	

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
	Air pressure DF: raster/polyline	Meteorological data (stations)	CRU Climate Datasets; GCM Downscaled Data Portal **NA:** Can be derived from remote sensing satellites (e.g. CALIPSO, CloudSat).	
	Albedo DF: raster	Reflectance data	NASA Earth Observations (NEO); MODIS products **NA:** Can be retrieved from remote sensing satellites (e.g. Landsat, Sentinel).	**Q1:** Shows the ability of the surface to reflect solar light, has a significant impact on soil moisture and regulates meteorological variables. **Q2:** Exposure. **Q3:** All levels.

Table 13. Transport and utility network

Category	Indicator (GIS data layer)	Potential source	Alternative web-based data	Questions (chapter 7.5)
Transport	Railway DF: polyline	National map services, organizational thematic maps	SEDAC; OpenRailwayMap NA: Can be extracted from remotely-sensed imageries and web-based map services.	**Q1:** Communication routes and networks are vulnerable and will be affected by SDS through accidents and cancellations. On the other hand, they can help people to communicate for better adaptation and mitigation. **Q2:** Sensitivity and adaptive capacity. **Q3:** All levels, mainly sectoral.
	Road DF: polyline	National map services, organizational thematic maps	OpenStreetMap; SEDAC; gROADS **NA:** Can be extracted from remotely-sensed imageries and web-based map services.	

Category	Indicator (GIS data layer)	Potential source	Alternative web-based data	Questions (chapter 7.5)
	Airline routes DF: polyline	IATA airline map and national airway maps	OpenFlights **NA:**--	
	Marine DF: polyline	National map services and organizational thematic maps	World Port Index **NA:** Can be extracted from remotely-sensed imageries and web-based map services.	**Q1:** These infrastructures will experience the reduction of their desired efficiency as SDS is increased. **Q2:** Sensitivity and adaptive capacity. **Q3:** All levels, mainly sectoral.
	Airport, harbours, bus terminals, train stations DF: point	National map services and organizational thematic maps	OpenStreetMap; OpenFlights; World Port Index **NA:** Can be extracted from remotely-sensed imageries and web-based map services.	
Utility network and facilities	Communication stations, electricity and gas stations	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	**Q1:** Utility networks will be negatively affected by SDS and influence vulnerability. **Q2:** Sensitivity. **Q3:** Local and sectoral.
	Power plants, electric power facilities and distribution lines	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	
	Telecommunication facilities and distribution lines (cables, networks)	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	

Table 14. Industrial facilities

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Essential facilities	Tourism and recreational facilities DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	**Q1**: They will be negatively affected by SDS and influence vulnerability. Q2: Sensitivity. Q3: Local and sectoral.
	Cultural and religious facilities DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK; United Nations Educational, Scientific and Cultural Organization (UNESCO) reports **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	**Q1:** They provide essential facilities for adaptation and mitigation to SDS. **Q2:** Adaptive capacity. **Q3:** Up to national level.
	Public facilities and governmental offices DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	
	Markets and shopping centres DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	
Industrial facilities	Factories DF: point	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	**Q1:** As SDS frequency increases, the industrial sector will experience the reduction of the labour-force efficiency, reducing product quality and increasing costs of cleaning. **Q2:** Sensitivity. **Q3:** All levels, mainly sectoral.
	Food industry DF: point	National map services and organizational thematic maps	OpenStreetMap; GEONETWORK **NA:** Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	

Table 15. Vegetation data

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Vegetation	Agriculture DF: raster/ polygon	National map services, cadastral and land-use maps	OpenStreetMap; SEDAC; EarthStat; GIAM; Global Land-Use Dataset **NA:** Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	**Q1:** Distinguish the different types of agro-economic activities which are sensitive to dust particles. They also have positive roles in reducing vulnerability by increasing adaptive capacity from the viewpoint of local community's economy. **Q2:** Sensitivity and adaptive capacity. **Q3:** All levels, mainly sectoral.
	Horticulture and orchard DF: raster/ polygon	National map services, cadastral and land-use map	OpenStreetMap; SEDAC; EarthStat; GIAM; USGS Land Cover **NA:** Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	
	Rangeland DF: raster/ polygon	National map services, natural resources and land cover map	Global Land-Use Dataset; SEDAC; USGS Land Cover **NA:** Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	**Q1:** Distinguish the different types of green coverage which are sensitive to dust particles. They also have positive roles in reducing vulnerability by absorbing suspended particles. **Q2:** Sensitivity. **Q3:** All levels.
	Forest DF: raster/ polygon	National map services, natural resource maps	Atlas of the Biosphere; GEONETWORK; UNEP WCMC; USGS Land Cover; Phased Array type L-band Synthetic Aperture Radar (PALSAR) forest/non-forest map, MODIS products **NA:** Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	

Table 16. Water and precipitation

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Water	Lakes, dams and water reservoirs DF: polygon	National map services, hydrological maps, organizational thematic maps	SEDAC; OpenStreetMap; Global Reservoir and Dam Database (GRanD); Global Lakes and Wetlands Database (GLWD) **NA:** Can be extracted from remotely-sensed imageries (e.g. MODIS and Landsat).	**Q1:** Distinguish the surface water bodies that need protection against dust pollutants deposition. In addition, they play a positive role in air humidity, wet deposition and air cooling. **Q2:** Sensitivity. **Q3:** All levels.
	Rivers and drainage network and canals DF: polyline	National map services, hydrological maps, organizational thematic maps	HydroSHEDS **NA:** Can be extracted based on topographic data (e.g. SRTM).	
	Wetlands DF: raster/ polygon	National map services	UNEP WCMC; GLWD NA: Can be extracted from remotely-sensed imageries (e.g. MODIS and Landsat).	**Q1:** Distinguish the different wetland ecosystems and the exposed flora and fauna. They have positive impacts on air humidity, wet deposition and air cooling. **Q2:** Sensitivity. **Q3:** All levels.
	Groundwater level DF: raster/ polygon	Groundwater maps	Global groundwater maps **NA:** Can be extracted from remotely-sensed imageries (e.g. GRACE).	**Q1:** The lower the groundwater level, the more vulnerable the land for SDS emission and the higher the vulnerability. **Q2:** Sensitivity. **Q3:** All levels.
Snow cover map	Average snow depth and snow cover DF: polygon/ raster	Snow depth and snow cover maps	Atlas of the Biosphere; MODIS products **NA:** Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel)	**Q1:** Snow depth and snow cover have impacts on vulnerability by absorbing SDS pollutant particles. **Q2:** Sensitivity. **Q3:** All levels.

Table 17. Soil and geomorphology

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Soil	Soil erodibility DF: raster/ polygon	Soil erodibility map	GEONETWORK; Atlas of the Biosphere; FAO soil maps; **NA:** can be calculated by soil erosion models (e.g. European Soil Erosion Model (EUROSEM))	**Q1:** The higher the soil erodibility, the higher the vulnerability to SDS. **Q2**: Sensitivity. **Q3:** All levels.
	Soil moisture DF: raster/ polygon	Soil moisture maps	Satellite-derived products such as Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) satellite maps **NA:** Can be extracted from remotely-sensed imageries.	**Q1:** Soil moisture and texture affect soil sensitivity to erosion and influence vulnerability. **Q2:** Sensitivity. **Q3:** All levels.
	Soil texture DF: raster/ polygon	Soil physical properties maps	GEONETWORK; World Soil Information; FAO soil maps **NA:** Can be extracted from remotely-sensed imageries.	
	Forest DF: raster/ polygon	National map services, natural resource maps	Atlas of the Biosphere; GEONETWORK; UNEP WCMC; USGS Land Cover; PALSAR Forest/ Non-Forest map, MODIS products **NA:** Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	
Geology and Geomorphology	Geological maps DF: raster/ polygon	National map services, organizational thematic maps	GEONETWORK; OneGeology Portal **NA:** Can be extracted from remotely-sensed imageries.	**Q1:** Provide information for SDS-VAM by contributing to soil erodibility map generation. **Q2:** Sensitivity. **Q3:** All levels.
	Geomorphology and Landforms DF: raster/ polygon	National map services, organizational thematic maps	OneGeology Portal **NA:** Can be extracted from GIS modelling by remotely-sensed imageries.	

Note: NA: No appropriate data are available.
DF: Data format.

Annex 2: Data available on the web

ACLED (http://www.acleddata.com/data) is a database that codes the dates and locations of all reported political violence and protest events in over 60 developing countries. Political violence includes events that occur within civil wars and periods of instability.

AERONET (https://aeronet.gsfc.nasa.gov/) provides globally distributed observations of spectral aerosol optical depth (AOD), inversion products and perceptible water in diverse aerosol regimes.

ASTER GDEM (https://asterweb.jpl.nasa.gov/gdem.asp) provide 30m resolution global elevation data derived from ASTER satellite images. ASTER GDEM coverage spans from 83 degrees north latitude to 83 degrees south, encompassing 99 per cent of Earth's landmass.

Atlas of the Biosphere (https://nelson.wisc.edu/sage/data-and-models/atlas/) provides information about the environment and human interactions with the environment including per capita oil usage, literacy rate, population growth rate, cropland and built-up land, soil pH, snow depth, snow coverage and more.

Barcelona Supercomputing Centre (https://ess.bsc.es/bsc-dust-daily-forecast) demonstrates the ongoing value of climate services, air quality services and dust services to society and the economy.

CGIAR-CSI (http://srtm.csi.cgiar.org/) is a geoportal that provides Shuttle Radar Topographic Mission (SRTM) 90m (and resampled 250m) digital elevation data (DEM) for the entire world. The SRTM DEM are originally produced by NASA and are considered among the most valuable elevation data worldwide.

CRU Climate Datasets (http://www.cru.uea.ac.uk/data/) provides a variety of available high- and low- resolution data sets including precipitation, temperature, pressure, drought.

DIVA-GIS (http://www.diva-gis.org/gdata/) contains a collection of spatial data worldwide, including administrative areas, inland water, roads, railways, elevation, land cover, population and climate. Spatial data have been collected from different sources and are available for any country in the world.

EarthStat (http://www.earthstat.org/) provides geographic data sets of the distribution of particular crops, water depletion and natural vegetation, among other data sets.

GADM (http://www.gadm.org/) is a spatial database of the location of the world's administrative boundaries including countries and lower level subdivisions.

GCM Downscaled Data Portal (http://www.ccafs-climate.org/data/) includes a wide range downscaled (higher-resolution) data created from the outputs of a wide range of global climate models. It contains the majority of important climate variables with a better spatial resolution.

GEONETWORK (http://www.fao.org/geonetwork/srv/en/main.home) A geographic information system (GIS) aggregation website including administrative and political boundaries, agriculture and livestock, applied ecology, base maps, remote sensing, biological and ecological resources, watersheds (river basins), climate, fisheries and aquaculture, forestry, human health, hydrology and water resources, infrastructures, land cover and land-use, population and socioeconomic indicators, soils and soil resources and topography.

GIAM (http://waterdata.iwmi.org/) contains information on global irrigated and rain-fed croplands, irrigation water sources (surface, groundwater), cropping intensity (single, double, continuous) and dominant crop types.

Global Aridity Index (https://cgiarcsi.community/data/global-aridity-and-pet-database/) provides global indices of aridity data and at 30 arc-second resolution in raster format.

Global groundwater maps (https://www.whymap.org/whymap/EN/Maps_Data/maps_data_node_en.html) is a spatial portal to provide data and information about the major groundwater resources of the world.

Global Lakes and Wetlands Database (GLWD) (https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database) is a portal including global maps of lakes, reservoirs, wetlands, swamps, and other environments.

Global Land Use Dataset (http://nelson.wisc.edu/sage/data-and-models/global-land-use/grid.php) includes a number of data sets showing population, land area, cropland area, land cover, land suitability for cultivation, grazing land area and built-up area at 0.5 degree resolution.

Global Reservoir and Dam (GRanD) Database (http://atlas.gwsp.org/index.php) is an online data set that compiles reservoirs with a storage capacity of more than 0.1 km^3. The data includes spatially explicit records of dams and reservoirs at high spatial resolution with extensive metadata.

Global Roads Open Access Data Set (gROADS) (http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1/data-download) is a data set of roads worldwide hosted by the Center for International Earth Science Information Network (CIESIN).

HydroSHEDS (https://www.hydrosheds.org/) contains hydrological data and maps extracted from the Shuttle Radar Topography Mission (STRM) elevation data including global river networks, watershed boundaries, drainage directions and flow accumulations.

MODIS products (https://modis.gsfc.nasa.gov/data/dataprod/) provides a rich data set of global atmosphere, land, cryosphere and ocean products. A great number of products are included, for instance, snow cover, aerosol products, cloud product, land cover, albedo and many more.

NASA Earth Observations (NEO) (https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA) provides Albedo data retrieved from satellite imageries.

Natural Disaster Hotspots (http://sedac.ciesin.columbia.edu/data/collection/ndh#) is a geoportal including a range of geographic data on natural disasters (including volcanoes, earthquakes, landslide, flood and 'multihazards') with hazard frequency and economic loss, among other indicators.

Natural Earth (http://www.naturalearthdata.com/) provides a convenient resource for making custom maps. It contains free vector and raster map data at 1:10m, 1:50m, and 1:110m scales. The data includes country borders, administrative maps, populated places, urban areas, water bodies and boundaries, islands, coastline, glaciated areas, land cover and shaded relief. Bear in mind that some data are only available for particular countries/continents.

OneGeology Portal (http://portal.onegeology.org/OnegeologyGlobal/) is a spatial portal including combined geological data from many geological organizations across the world. Basic geological data are available for many countries.

OpenFlights (https://openflights.org/data.html) contains airports, airline routes, train stations and ferry terminals spanning the globe.

OpenRailwayMap (http://www.openrailwaymap.org/) is a detailed online map of global railway infrastructure, built on OpenStreetMap data.

OpenSeaMap (http://openseamap.org/index.php?id=openseamapandno_cache=1) provides online map of global marine ways, built on OpenStreetMap data.

OpenStreetMap (http://www.geofabrik.de/data/download.html) is a crowdsourced database including a number of GIS-ready shapefiles such as urban extent, administrative boundaries, roads, points of interest, buildings and ferry routes.

PALSAR Forest/Non-Forest map (http://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm) Global 25m resolution PALSAR-2/PALSAR Mosaic and Forest/Non-forest map of a freely available dataset generated by applying Japan Aerospace Exploration Agency (JAXA)'s powerful processing and sophisticated analysis method/techniques to several images obtained with Japanese Phased Array type L-band Synthetic Aperture Radars (PALSAR and PALSAR-2) on Advanced Land Observing Satellite (ALOS) and Advanced Land Observing Satellite-2 (ALOS-2).

Protected Planet (https://www.protectedplanet.net/) is a publicly available online platform where terrestrial and marine protected areas and access-related statistics can be explored and downloaded.

Socioeconomic Data and Applications Center (SEDAC) (http://sedac.ciesin.columbia.edu/) is a data centre in NASA's Earth Observing System Data and Information System (EOSDIS) hosted by CIESIN at Columbia University. It provides a range of socioeconomic spatial data, including settlement points, urban areas, environmental indicators (annual maps of $PM_{2.5}$, urban heat islands, land surface temperature, NO_2 concentrations), spatial economic data, population density, population, global anthropogenic biomes, roads, agricultural lands, water bodies, poverty maps (for 28 countries) and many more regional and local data (log in required).

UNEP GEOdata (http://geodata.grid.unep.ch/) is the authoritative source for data sets used by United Nations Environment Programme (UNEP) and its partners in the Global Environment Outlook (GEO) report and other integrated environment assessments. Its online database holds more than 500 different variables, as national, subregional, regional and global statistics or as geospatial data sets (maps), covering themes like fresh water, population, forests, emissions, climate, disasters, health and GDP.

UNEP WCMC (http://datadownload.unep-wcmc.org/datasets) includes a wide range of data sets from the United Nations Environment Programme (UNEP) World Conservation Monitoring Centre such as global wetlands, global distribution of coral reefs, mangrove distributions, tropical dry forests, wilderness, global distribution of saltmarshes and more.

Uppsala Conflict Data Program (UCDP) (http://ucdp.uu.se/) is an online map presenting the location and statistics of instances of political violence in different parts of the world.

USGS Land Cover (https://www.usgs.gov/core-science-systems/science-analytics-and-synthesis/gap/science/land-cover-data-download?qt-science_ center_objects=0#qt-science_center_objects) is a very useful web page providing a great number of links to many land cover, forestry, albedo, agriculture, river observations and many more data sets.

WMO GAWSIS (https://gawsis.meteoswiss.ch/GAWSIS/#/). The World Meteorological Organization (WMO) Global Atmosphere Watch Station Information System.

WMO OSCAR (https://www.wmo-sat.info/oscar/). The Observing Systems Capability Analysis and Review Tool (OSCAR) is the WMO's official repository of WIGOS metadata for all surface-based observing stations and platforms.

WMO SDS-WAS (https://sds-was.aemet.es/) and (https://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html). WMO Sand and Dust Storm Warning Advisory and Assessment System.

WMO WIGOS (https://www.wmo.int/pages/prog/www/wigos/index_en.html). WMO Integrated Global Observing System.

World Bank Geodata (http://databank.worldbank.org/data/home.aspx) includes a wide range of global data such as population, financial data, education statistics and indicators, gender statistics, health nutrition and population statistics and many more data sets.

World Port Index (http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=trueand_pageLabel=msi_portal_page_62andpubCode=0015) is a database that contains the location and physical characteristics of, and the facilities and services offered by, major ports and terminals worldwide.

World Soil Information (https://www.isric.org/) is a geoportal that provides soil information on national and/or local levels. Gridded datasets covering the world's soils at a maximum resolution of 5 arc-minutes with 22 attributes for each cell including organic carbon content, clay content, silt content, sand content and water capacity.

WorldClim (http://www.worldclim.org/) is a set of global climate data (temperature (min, max, mean) and precipitation) with a spatial resolution of about 1 km^2. Climate data are available from the past, present and predicted data for future conditions.

WorldPop (http://www.worldpop.org.uk/) is an open access database of high spatial resolution, contemporary data on human population distributions for most parts of the world.

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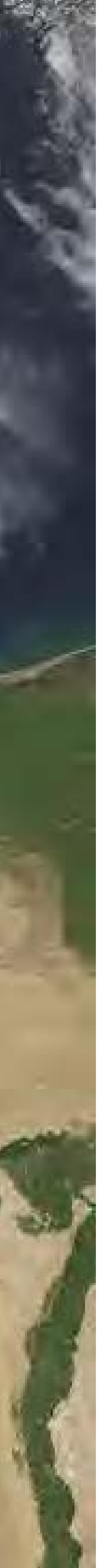


8. Sand and dust storm source mapping

Chapter overview

This chapter provides extensive details on how to map potential sand and dust storm (SDS) source areas based on the nature of the soil. The chapter covers drivers of SDS source activity, anthropogenic sources, the distribution of SDS sources and two approaches to SDS source mapping. The chapter includes a process for high-resolution SDS source mapping based on soil and surface data, provides formulae for this type of analysis and includes a list describing data sources which can be used in the SDS source mapping process. This chapter is to be read in conjunction with chapter 2.

8.1. Overview of the physical sources of SDS

Based on the information compiled from Lu and Shao (2001), Shao (2008) and United Nations Environment Programme (UNEP), World Meteorological Organization (WMO) and United Nations Convention to Combat Desertification (UNCCD) (2016), the primary source of sand and dust storms (SDS) can be defined as “a bare topsoil surface susceptible to wind erosion or any surface capable of emitting soil particles in favourable wind conditions”. “Bare topsoil” is a soil surface fraction without vegetation or snow/ice cover or that is covered by a water body (for example, a lake, river or wetland).

A soil surface is susceptible to wind erosion when it contains smaller soil particles, generally clay and silt size particles up to about 50–60μm in diameter, depending on the classification system (Schaetzl and Anderson, 2009). In case of high surface wind velocity, sand size particles (predominantly very fine sand of up to about 100 μm in diameter) may be emitted from a surface and carried away, but over much shorter distances than finer particles.

The likelihood of soil becoming part of an SDS event is increased if the soil structure is disturbed and loose, leading to particles being free for uptake by wind. Other conditions that can contribute to soil becoming part of an SDS event include:

- low topsoil moisture
- the soil not being frozen
- surface wind velocity above a certain threshold closely related to particle size distribution in topsoil and topsoil moisture (see **chapter 2**)

SDS source locations and conditions are distinguished by the nature of the source:

- **Permanent SDS sources** are mostly located in desert areas and are constantly susceptible to wind erosion given their fine (small μm) topsoil content, permanent warm and arid climate, no or limited vegetation cover and the general absence of water bodies.
- **Dynamic SDS sources** can change in the level of SDS-related activity depending on the season, weather conditions and human impacts.

The dynamics of SDS sources are related to seasonal changes in the vegetation cover, snow cover, the existence of or changes in the extent of water bodies and whether the soil is frozen. These variations create notable changes in SDS source geographic distribution.

Dynamic SDS sources range from “seasonal” to “occasional”. “Seasonal” sources are usually controlled by climatological seasonality in weather conditions and “occasional” sources are the ones not necessarily active during favourable seasonal conditions, but which require an additional driver to trigger their activity, usually extreme weather and/or direct human impacts. SDS sources may evolve into sources with different temporal activity, meaning they may change from occasional to seasonal or permanent, or vice versa, depending on the impacts of drivers of SDS source activity. Determining the likelihood of such behaviour requires regular monitoring of SDS sources.

Drought, as an extreme seasonal or multi-season weather condition, may lead to SDS or an increase in SDS activity. Heat waves may prevent freezing of topsoil and contribute to increased SDS activity. For additional details on permanent and dynamic sources, see Kim et al. (2013), Vukovic et al. (2014), Tegen (2016), WMO and UNEP (2013) and UNEP, WMO and UNCCD (2016).

Human interventions can have positive or negative impacts on SDS source activity. Sustainable land management practices, such as afforestation and climate smart agriculture (Sanz et al. 2017), may reduce the likelihood of SDS (**see chapter 12 and 8.3**).

On the other hand, anthropogenic impacts that can induce and increase vulnerability of topsoil to wind erosion come from different sectors of the economy and include direct and indirect impacts. This is discussed further in **chapter 8.3**.

Identifying and mapping SDS sources, and understanding why these locations produce SDS, provides information for SDS risk and impact assessment, SDS mitigation planning, SDS forecasting and establishment of SDS early warning systems (WMO and UNEP, 2013) (see **chapters 5, 6, 7, 9, 10, 11** and **12**). Mapping the spatial and temporal distribution of SDS sources requires:

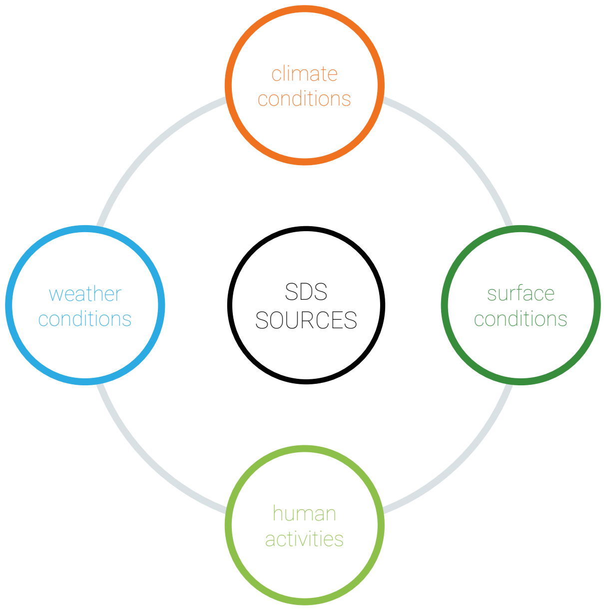
- understanding what causes the formation and activation of SDS sources (see **chapter 8.2**)
- defining parameters for SDS productive areas (see **chapter 8.2**).
- understanding ways to adjust SDS mapping procedures to provide useful information

A proposed methodology to detect the surface potential for SDS formation is described in **chapter 8.5**.

8.2. Drivers of SDS source activity

Four drivers impact the existence of SDS sources, as summarized in **Figure 22** and discussed herein. Each driver interacts with each of the other drivers. This interaction can vary in time and space and may lead to an increase or decrease in SDS generation. **Climate conditions:** Climate is one of the main drivers of the formation of permanent SDS sources in desert areas (Shao 2008; Shao et al., 2011).

Figure 22. Drivers that impact sand and dust storm activity



Extreme aridity, together with high winds in desert areas with insufficient vegetation and long-term exposure to erosion, can lead to the formation of SDS sources. Climate conditions also affect seasonal activity of SDS sources, which is related to seasonal change of surface conditions – mainly of vegetation cover – and seasonal winds (Kim et al., 2013; Tegen, 2016).

Weather conditions: Weather conditions can induce additional SDS source activity and lead to the formation of new SDS sources. Consistent or repetitive dry weather conditions with seasonal wind patterns is distinguished as a separate driver from climate conditions. At the same time, changes from usual SDS source behaviour can be the result of extreme weather conditions, which become more common in a world where the climate is constantly changing (Intergovernmental Panel on Climate Change [IPCC], 2012; 2014a). Meteorological drought is an example of extreme weather and can cause increased SDS source activity.

However, the true effect of drought also depends on other drivers (**Figure 22**) which can amplify or reduce the impact of drought. In mid- and higher latitudes heat waves may trigger the activity of SDS sources during the season when the surface is usually frozen or covered by snow. This effect is expected to increase in the future under the changing climate conditions.

Wind speeds which vary from usual seasonal atmospheric circulation are also an element in the weather driver package. For example, during extreme surface heating or intense cold frontal movement, formation of strong convective activity is possible. This can produce cold downdrafts from clouds and, consequently, high surface winds that increase SDS source activity in the event of low humidity conditions (Knippertz et al., 2009; Knippertz and Todd, 2012; Vukovic et al., 2014). Terms associated with such events are “haboob”, “line of instability”, “cold pool” and “density currents”.

Surface conditions: Surface conditions are soil characteristics (most importantly soil texture and structure), soil condition (moisture and temperature), and land cover (bare soil fraction). Soil texture with a fine particle content is a precondition for a location becoming an SDS source. If soil structure is disturbed, topsoil particles are more susceptible to wind erosion where soil moisture is low and soil temperature is above freezing (Kok, 2011; Kim et al., 2013; Wu et al., 2018). Bare soil surface is a precondition for the existence of active SDS sources, which means there is no vegetation, snow/ice or water on the topsoil. Areas that include fractions of bare soil surface, like sparsely vegetated area, are considered as SDS sources, with less possibility of dust emission compared to fully bare land areas.

Due to the complexity of the ways surface conditions and soil surfaces respond to other drivers, and their large spatial and temporal variability (including many unknown processes), it is better to distinguish surface conditions as a separate driver. Expanding knowledge of soil composition can strongly contribute to understanding of these interactions, as well as the understanding of SDS impacts on humans and the environment (Nickovic et al., 2012; 2013; Sprigg et al., 2014).

Human activities: Interaction of humans with natural processes can lead to amplification or suppression of other drivers.

Direct impacts of human activities include change of surface conditions. Water scarcity, tillage, grazing and deforestation can have a direct impact on soil degradation (Orr et al., 2017) and thereby result in the amplification of SDS source activity. Sustainable land management practices (Sanz et al., 2017; Orr et al., 2017) can reduce SDS activity. Indirect impacts of humans on SDS activity include the anthropogenic impact on the climate which affects the other drivers of SDS source activity.

Human activities are a significant driver for changes in the whole climate system, with increasing world population and global warming currently the two largest stressors for the environment. The human impact is measured as a planetary-scale geological force (Diffenbaugh and Field, 2013; Steffen et al., 2015; Cherlet et al., 2018). This is the reason for separate analysis of SDS sources, which exist mainly as a consequence of human activities, as described in **chapter 8.3**.

8.3. Anthropogenic sources

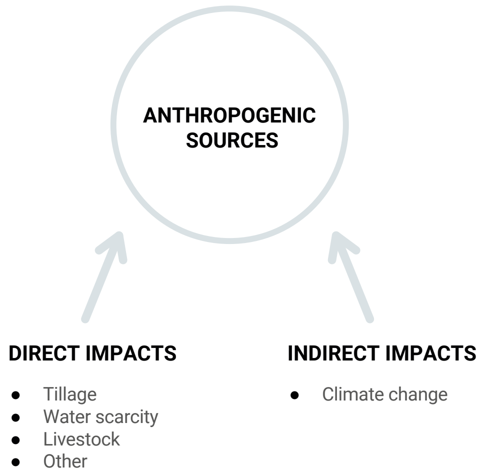
Human activities have a significant impact on the climate system (IPCC, 2014b) and especially on land surface characteristics by transforming them to surfaces suitable for food production and other economy benefits (IPCC, 2019).

These activities can impact SDS source formation and increase the activity of dynamic SDS sources, possibly transforming them into permanent source areas (UNEP, WMO and UNCCD 2016; United Nations Economic and Social Commission for Asia and the Pacific [UN ESCAP], 2018). Enhanced emissions can cause severe negative impacts on the environment, human health and safety (Pauley, Baker and Barker et al., 1996; Arizona Department of Environmental Quality, 2012; Sprigg et al., 2014; Irfan et al., 2017).

When human activities are the predominant driver of SDS source activity, these SDS sources are called "anthropogenic sources". The human activities which contribute to anthropogenic sources occur in multiple sectors, including agriculture, water, forestry, energy and transport. Anthropogenic sources can result in "direct" and "indirect" impacts. Factors with "direct impacts" that have the most effect on SDS source activity are:

- land cover changes, disturbance of the topsoil and loss of soil structure, which are mostly the consequence of agriculture practices (tillage and livestock breeding).
- use of water for irrigation, hygienic needs (especially for large urban areas) and industry.
- other factors that can dominate impact in some regions, such as deforestation, fires, mining.

Figure 23. Most relevant human impacts leading to sand and dust storm anthropogenic sources



Human activity-related climate change has an impact on an increased frequency and intensity of severe weather events, like drought, fires and high winds, and thereby can have "indirect impact" on SDS source activity (IPCC 2012; 2014a). The most important impacts which lead to the formation of anthropogenic sources are shown in **Figure 23**.
Recognizing and acknowledging the human impact on SDS source activity and understanding the impact of SDS generated from anthropogenic sources is important for SDS source mitigation planning and implementation. Prioritizing mitigation of anthropogenic sources considers restoration of the natural dust cycle in the climate system and achieving land degradation neutrality. Assessment of climate change impact on SDS source activity contributes to adaptation planning in areas vulnerable to SDS.

8.4. Distribution of SDS sources

Knowledge on SDS source distribution is an initial step for assessment of risk and impact of SDS and implementation of SDS source mitigation measures. Distribution and patterns of dust sources are complex and have high spatial and temporal variability, which is the consequence of the high spatial variability of topsoil texture and structure, land-use, socioeconomic impacts and variability of climate and weather conditions.

Spatial scales of SDS sources range from large-scale erodible areas in desert regions to point-like sources usually sensitive to agriculture practice and water scarcity (Shao et al., 2011; Lee et al., 2009 ; Ginoux et al., 2012; Vukovic et al., 2014), as well as the retreat of glaciers and occurrence of high-latitude SDS events (Bullard et al., 2016; Arnalds, Dagsson-Waldhauserova and Ólafsson, 2016). A dense pattern of point-like sources may individually emit dust plumes that merge into a larger-scale SDS event, which may reach the significance of emissions from large-scale sources.
Areas and locations that have the best conditions (drivers) for SDS generation and that produce a major share of airborne sand and dust concentrations are called "hotspots" (Engelstaedter and Washington, 2007). This type of source is usually:

- small in scale and situated in larger-scale SDS productive areas (Lary et al., 2015; Feuerstein and Schepanski, 2019), or
- distributed as individual sources outside desert areas (Lee et al., 2003; Arnalds, Dagsson-Waldhauserova and Ólafsson, 2016).

The global and regional distribution of major SDS source areas has been covered in detail in several reports, including WMO and UNEP (2013) and UNEP, WMO and UNCCD (2016). The main SDS productive source areas are situated in the desert belt in the northern hemisphere (Central Asia, the Middle East, North Africa). Other notable SDS productive areas are in south-west part of the United States of America (USA), the southern part of South America, south Africa and Australia. See **chapter 2** for more information on SDS source areas.

8.5. SDS source mapping

8.5.1. Two approaches to detecting SDS source areas

Understanding where to implement SDS source reduction actions requires knowing where SDS can originate and how sand and dust can be entrained into SDS events (Middleton and Kang, 2017). Two major factors that influence the generation of SDS are high surface winds and a free-soil surface.

High surface wind velocity can be a consequence of seasonal patterns of large-scale atmospheric circulation and/or extreme local weather conditions (see **chapter 8.2**). A "free-soil surface" is relatively dry, unprotected topsoil (free of vegetation, snow, ice or water), which is not frozen, the soil particles of which are free to be emitted under windy conditions. As surface winds of sufficient velocity for soil particle emission are common in all parts of the world, SDS generation is determined in a significant way by the existence of a free-soil surface.

SDS source mapping can be divided into two approaches:

1. SDS source mapping from data on SDS occurrence
2. SDS source mapping from data on surface conditions

These two approaches are discussed as follows.

8.5.2. Sand and dust storm source mapping based on sand and dust storm occurrence

SDS source mapping based on SDS occurrence uses data on SDS occurrence, such as satellite data, ground PM measurements and visibility data (Wang, 2015). Results are better if longer periods of data are included in the analysis.

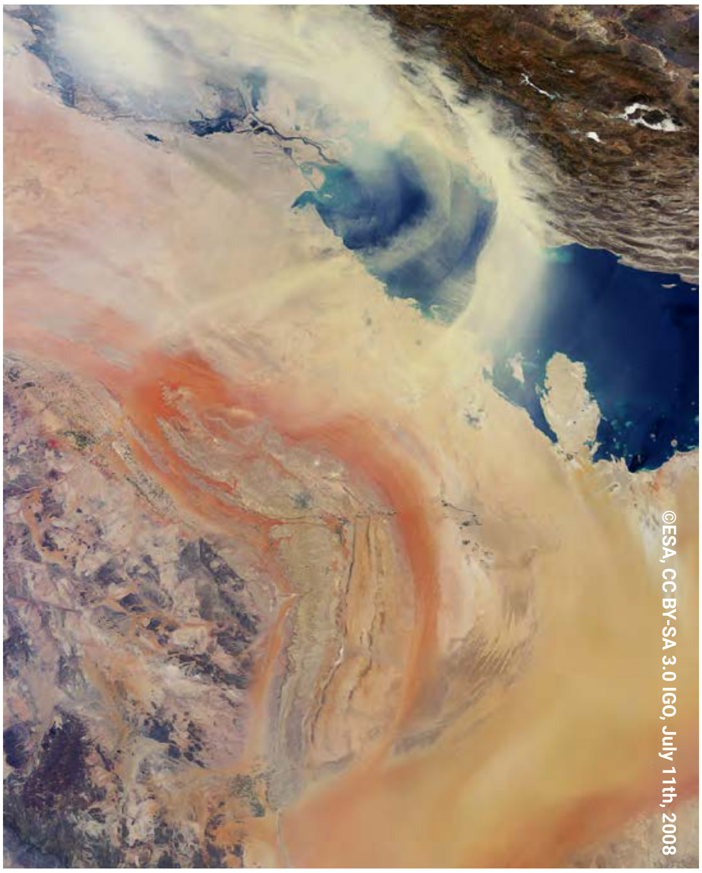
Global distribution of SDS sources obtained using this approach can be found in Shao (2008), Shao et al. (2011) and Ginoux et al. (2012). Remotely-sensed data and machine learning can generate relatively high-resolution point-like sources (Lary et al., 2015). The advantages and disadvantages of mapping based on data on SDS occurrence are listed in **Table 18**.

Table 18. Advantages and disadvantages of sand and dust storm mapping using sand and dust storm occurrence

Advantages	Disadvantages
• Good representation (high confidence) of synoptic overview of major and frequently active sand and dust storm (SDS) sources (permanent and seasonal). • Recognize global and regional sources that are dominant in SDS generation.	• It represents mapping of SDS activity (or occurrence), not SDS sources. • Spatial and temporal coverage of SDS observations is not continuous. • Resolution is lower than mapping resolutions of other soil surface related parameters. • Unable to recognize/delineate many of small-scale and, occasionally, active SDS events. • Climatological approach (averaging of long-term data) gives advantage to natural (permanent and seasonal) and/or larger scale SDS sources. • Underestimates SDS sources which are small scale and/or not frequently active.

8.5.3. SDS source mapping of data on soil surface condition

This approach to SDS source mapping uses a combination of data on the potential for the soil surface to emit soil particles which can be carried away from source in favourable wind conditions, that is, the soil surface's susceptibility to wind erosion.



The approach is based on use of soil and surface data to estimate (parameterize) information on soil surface potential to produce SDS, rather than to detect SDS occurrence.

The SDS source mapping based on soil conditions is used, for example, in mapping SDS sources in numerical modelling of dust transport (Nickovic et al., 2001; Kim et al., 2013; Vukovic et al., 2014), and in studies that investigate the level of land degradation and desertification (UNCCD, 2017; Cherlet et al., 2018). This approach to SDS source mapping is less used due to its complexity.

However, the approach can significantly contribute towards the better definition of SDS source patterns, including their small-scale features, which is necessary in planning actions related to SDS source mitigation. Advantages and disadvantages of mapping based on data on soil surface conditions are listed in **Table 19**.

Table 19. Advantages and disadvantages of sand and dust storm mapping based on soil conditions

Advantages	Disadvantages
▪ Contains data on soil characteristics and land-use. ▪ Can provide high-resolution SDS source patterns. ▪ Can detect/delineate small-scale sources and distinguish SDS source hotspots. ▪ Can detect surfaces with high potential for SDS generation in extreme weather conditions, even if they are not frequently active.	▪ Requires a relatively complex combination of information from different sources of data. ▪ Due to high spatial variability and insufficient soil sampling, the quality of soil information may be low, which requires implementation of additional information. ▪ Does not include information on frequency of SDS generation.

Information on SDS sources based on SDS observations can be used to verify the reliability of data obtained from surface observations over larger SDS source regions. A good – and relatively simple – example of this methodology is SDS source mapping using topography data which is verified using satellite data, found in Ginoux et al. (2001), and later improved with seasonal SDS source change, found in Kim et al. (2013).

Overcoming the disadvantages of this approach involves:

- acquiring more accurate national data
- additional national observations and data sets
- methodologies that enable even higher resolution mapping.

A basic methodology for SDS source mapping using surface data, with possible map upgrades depending on data availability and quality, is discussed in more detail in **chapter 8.6**.

8.5.4. Gridded data on SDS sources

"SDS source mapping" means representation of geo-referenced data on SDS sources on a regular grid with certain resolution, where one number represents information about the SDS source in a grid box with dimensions that depend on the map resolution. Usually, information on the SDS source is scaled to have values from 0 to 1 (where 0 is no SDS source in the grid box and 1 is the whole area in the grid box being fully SDS-productive and/or have highest potential for SDS generation) or in percentage terms (0–100%).

Depending on the approach used for SDS source mapping, the data obtained can have different meanings.

1. When SDS source mapping is done using data on SDS occurrence (Prospero et al., 2002; Walker et al., 2009; Ginoux et al., 2012; Akhlaq et al., 2012; Shao et al., 2013; Division of Earth & Ecosystem Sciences, 2013; Sinclair and Jones, 2017), gridded information on SDS sources is usually derived from the frequency of SDS detection. Thereby, this kind of map represents frequency of SDS activity, assuming that areas with the highest frequency are the strongest sources of SDS, which corresponds to close to one in the SDS source map. In this case, SDS source hotspots are areas with the highest frequency of SDS occurrences.
2. When SDS source mapping is carried out using data on soil surface conditions, gridded information on SDS sources represent the potential of the soil surface in the grid box to emit particles in the event of high wind conditions. Thereby, this kind of map represents a fraction of the free-soil surface in the grid box. Values closer to one represent areas that are highly susceptible to wind erosion in cases of high surface velocity winds. In this case, SDS source hotspots are the surfaces with higher potential for emission of particles.

On climate scales, areas with the most frequent SDS occurrences will coincide, in a large part of the world, with areas with the highest potential for SDS generation. Because of their dynamic component caused by the change in SDS source drivers (see **chapter 8.2**), over larger timescales, SDS source map patterns can be significantly different, especially during extreme weather events that can trigger the activation of SDS source hotspots.

Such SDS sources can have low frequency of activity and are could possibly not be recognized as hotspots in the mapping approach that uses data on SDS occurrence, but must be recognized as having a high potential for SDS generation in mapping approaches that use data on surface conditions. For this reason, and due to direct and indirect human impacts on SDS formation (see **chapter 8.3**), mapping of SDS sources for the purpose of mitigation planning, forecasting of SDS and early warning systems, should consider applying a methodology based on soil surface data.

8.6. Methodology for high-resolution SDS source mapping

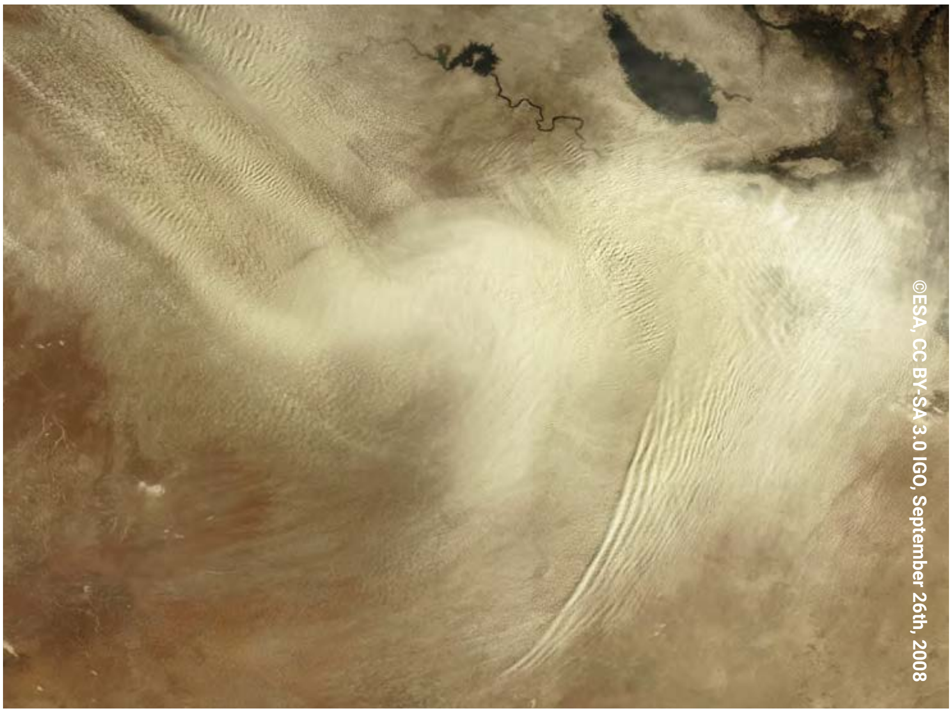
This section explains a methodology that enables high-resolution SDS source mapping, which relies on the approach discussed in **chapter 8.5.2**. It is based on available global data, which may be supplemented or replaced with national data of higher accuracy and resolution, if available, or may be supplemented with additional information available on national level, like SDS source hotspots.

8.6.1. Clusters of relevant data

Implementation of a methodology based on soil surface data analysis is necessary to achieve high-resolution SDS source mapping (at a 1 km or higher level of detail) which includes all areas that have the potential to generate SDS in favourable wind conditions.

A list of basic (most important) parameters that are required in SDS source mapping is presented in **Figure 24**. These parameters represent clusters of data sets, which are combined using certain criteria, mainly based on setting threshold values that serve the purpose of eliminating non-productive areas from the global land surface.

Therefore, this approach to SDS source mapping may be understood as an elimination method – excluding areas that are certainly not SDS-productive. The remaining areas represent potentially SDS-productive surfaces, which should include all permanent and dynamic (seasonal and occasional) sources.



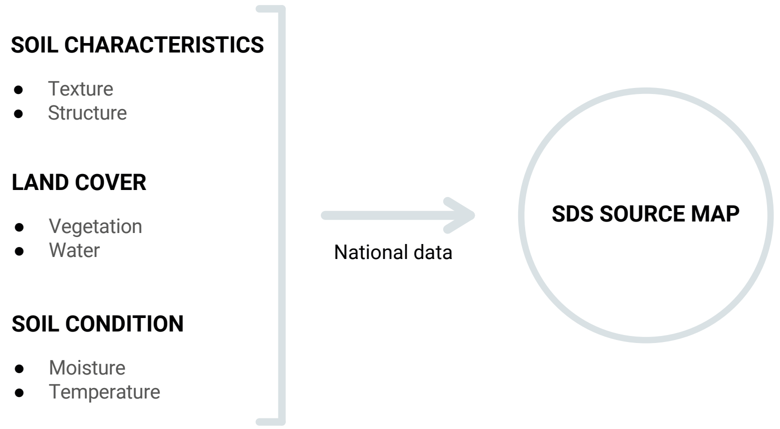


Figure 24. Soil surface parameters necessary for sand and dust storm source mapping

Note: Use of national data, if available, can improve the result of SDS source mapping at subnational and national scales, based on global data sets.

An initial cluster of parameters that are necessary for SDS source mapping (**Figure 24**) includes:

- data on soil characteristics
- data on land cover
- data on soil condition

Here are separated soil characteristic and soil condition data, where:

- "characteristics" describes soil as a material (texture, composition, etc.), and
- "condition" describes the soil properties which change according to seasonal and weather conditions.

Both can be impacted by human activities (see **chapter 8.2 and 8.3**).

Data that can provide information about listed parameters are universally available, but quality may differ from region to region. To further increase the quality of SDS source maps, implementation of national data and information is necessary.

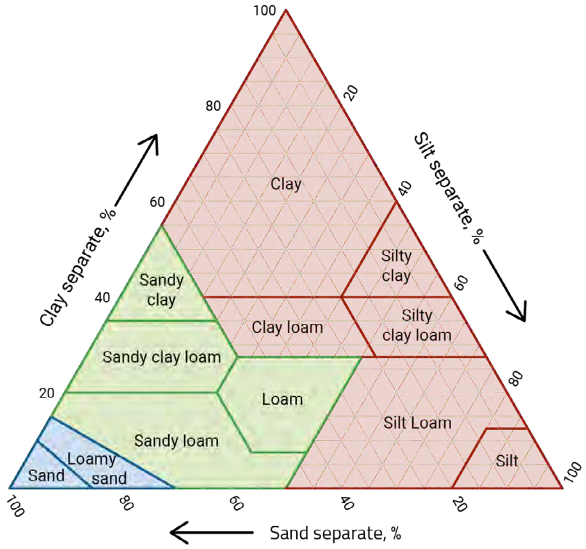
Soil characteristics

The most important information regarding soil characteristics is the soil texture and soil structure. Surface soil texture will provide information on soil particle size distribution, such as whether the soil contains particles that are small enough to be uplifted from the surface and carried away from the source (Lu and Shao 2001; Shao, 2008).

Such soil texture classes, based on the United States Department for Agriculture soil classification system,[1] are presented in **Figure 25**. Soil texture classes should include clay and silt size particles, but classes that have major part of sand size particles will not be ignored, just will be considered as less productive, because of their significant role in emission processes (Shao 2008; Sweeney et al., 2016). The most SDS productive soils, considering soil texture, are marked in red in **Figure 25**, medium productive in green and least productive in blue.

1 See https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/.

Figure 25. United States Department of Agriculture soil texture classification system



Key: Red – soil texture classes with higher content of fine soil particles. Green – soil texture classes with medium to low fine soil particles content, Blue – dominant coarse soil texture.

Note: Adapted from Natural Resources Conservation Service (n.d.).

Information on the surface soil structure provides information on whether a soil surface is disturbed or loose. Aggregate stability is related to organic matter content (Chaney and Swift, 1984). Soil that has low structural stability is found to have very low content of soil organic carbon (SOC). Desert areas have values of about 0.2 per cent and other areas in arid climates about 0.5 per cent (Fan Yang et al., 2018).

Soil organic carbon is one of the indicators used to assess land degradation and monitor land degradation neutrality (Cowie et al., 2018). Degraded soils are vulnerable to wind erosion, a land degradation process linked to SDS source formation.

Usually, fine soil texture is related to richer SOC content (Meliyo et al., 2016; Johannes et al., 2017), but where there is a fine structure and low SOC, surface soil particles can be loose where other parameters show favourable conditions for the activation of SDS sources. Setting upper SOC thresholds can exclude surfaces that have good surface structure and where soil particles are in stable condition. Low values or decreasing SOC values can serve to identify areas with increasing exposure to wind erosion, and which can become SDS sources.

The depth to bedrock can be one more limiting parameter categorized under soil characteristics (Shangguan et al., 2016). If the soils are shallow, they are most likely not significant SDS sources. Other soil characteristics that are indicative of its mineral and biochemical composition are important for understanding the interaction of particles with the environment, and their impact on climate system and humans. However, such information is very scarce.

Only a few data sets on soil characteristics related to SDS generation are available on a global level (Nickovic et al., 2012; Journet, Balkanski and Harrison, 2014; Perlwitz, Pérez García-Pando and Miller, 2015), and the available information can be improved. Soil data in global data sets can be of low quality and not regularly updated. Improving soil data sets can be done using national-level data, which are, however, usually not publicly available.

Land cover

Land cover data can be used to identify surfaces that are bare or sparsely/partially vegetated, and without snow/ice cover or water bodies (Tegen et al., 2002; Kim et al., 2013; Vukovic et al., 2014).

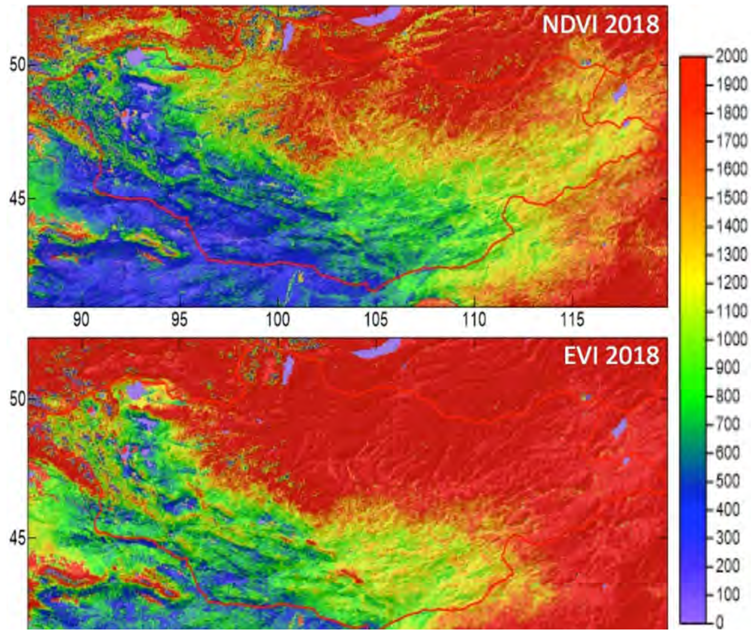
This information can be derived from regularly updated satellite data to detect changes in the activity of SDS sources. Parameters that can provide this kind of information are Normalized Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) data.

Land cover or land-use data are usually updated annually and can provide information about the type of surface (forest, grassland, cropland, bare, urban). Land cover types that can be considered potentially dust-productive are (i) bare land or (ii) sparsely vegetated land, grassland, scrubland and cropland. Other land cover types that can also be impacted by human impact drivers (see **chapter 8.3**.) can become anthropogenic sources due to the loss of ground cover, due, for example, to melting ice, fire or deforestation.

Land cover data can be used to detect bare regions but are insufficient for detecting dynamic SDS sources. As a result, land cover data can be used together with NDVI/EVI data to detect types of SDS source.

A priority in SDS source mapping, related to land cover analysis, is to use NDVI or EVI data and land cover data in a more diagnostic manner to recognize types of the SDS sources. NDVI data are commonly used for SDS source mapping, but EVI can correct some distortions arising from atmospheric haze and ground cover below vegetation (Heute et al. 2002).

Figure 26 presents an example of NDVI and EVI data for 2018 for Mongolia where differences between these two indices are clearly visible. Red values represent areas covered with vegetation and blue values areas without vegetation. Updated SDS source maps at a national level based on NDVI/EVA data can be used to identify different types of the SDS source (pasture, mining, among others).



Note: Values are multiplied by 104.
Source: Personal communication, courtesy of Jungrack Kim

Figure 26. Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index (MODIS NDVI) and Enhanced Vegetation Index (EVI) for 2018

Soil condition

The most important parameters related to soil condition, which are mainly related to weather conditions but can also be impacted by human activities, are (i) soil moisture and (ii) soil temperature. These parameters are discussed as follows.

If topsoil with favourable soil characteristics is dry enough and not frozen, emission from the surface is possible in favourable windy conditions. If topsoil is drier, the wind velocity threshold for emission of particles is lower (Bagnold, 1941; Fécan, Marticorena and Bergametti; Nickovic et al., 2001; Pérez García-Pando et al., 2011). Soil temperature needs to be well below 0°C to be frozen, and the threshold may depend on soil composition (Kim et al., 2013). Soil freezing temperature also depends on moisture content, because low-moisture soils need lower temperatures to freeze, and in soil saturated with water, will most likely freeze at temperatures near 0°C.

Setting an upper threshold for moisture data and a lower threshold for temperature data will distinguish areas that can generate SDS if other parameters allow classification of these areas as SDS sources. More about data sources and data manipulation can be found in the next section.

Other data and improvements of sand and dust storm source mapping

Necessary data for SDS source mapping described in the previous section are available on a global level or can be derived from global data sets. At regional and national levels, further improvements of data quality and resolution are possible for most of the listed parameters, using regional and national data sets (**Figure 24**), such as soil types and composition, soil condition data, weather and climate data and information on human activities (Gerivani et al., 2011; Cao et al., 2015; Borrelli et al., 2016). Better diagnostics on SDS source types are also possible, especially of anthropogenic sources, for example, mining sites, conventional agricultural production sites, glacier retreat zones or loss of vegetation due to fires. Mapping of SDS sources at the national level, including spatial and temporal resolution improvements, can be done by implementing SDS source monitoring using remote sensing and high-resolution topographic and geomorphological information (Bullard et al., 2011; Parajuli and Zender, 2017; Feuerstein and Schepanski, 2019; Iwahashi et al., 2018). Improvements of SDS source mapping by implementation of topographic data are discussed in more detail in **chapter 8.6.4**.

8.6.2. Calculating the SDS sources spatial distribution

Calculations can be used to identify the likelihood of SDS source development based on a range of factors, including soil texture, soil structure, bare soil surface, soil moisture and frozen soil. Calculation processes described below focus on extracting and processing data to develop SDS source maps. The calculations detailed below are based on an assumption that land surface can be SDS-productive (land is SOURCE=1) and continues with filtering using values for the soil surface parameters explained as follows.

Soil texture

Data on soil texture provides the fraction (percentage) of clay and silt content. Higher clay and silt content mean higher potential for SDS formation. The United States Department of Agriculture (USDA) soil texture types that have fine particle contents sufficient for blowing dust and SDS formation, can have total clay and silt content mainly above 50 %. Surfaces with sand-dominant content should not be excluded but rather scaled as less productive than surfaces with higher content of clay and silt, because heavier particles less contribute to emission rates during high wind events and require higher wind velocities to carry them away from sources.

Setting up the lower threshold on total clay and silt content will exclude surfaces that are not significantly active because of the very high, coarse fraction content. Scaling soil texture potential for SDS formation is directly related to finer particle content:

SOURCE = FTX , if FTX < FTXmin then set FTX = 0

where FTX is a fine soil texture fraction with values 0 to 1. Threshold FTXmin is not necessary, as lower FTX values will reduce SOURCE function. However, adjusting threshold value may exclude surfaces that are insignificant, for example, for transport far from the source and long-range transport.

Soil structure

To distinguish soils with a loose surface, meaning that particles on the surface are more susceptible to wind erosion, values of SOC can be used. Arid and desert surfaces have low SOC content, well below 1 per cent (0.2–0.5 per cent), but for vulnerable areas that are experiencing soil degradation and can transform into SDS sources, SOC can be up to 1 per cent. SOC information is implemented in SDS source mapping by defining the upper threshold, and all soil surfaces with lower values can be considered to have unstable or low structure, and thereby susceptible to wind erosion:

$$\text{SOURCE} = \text{FTX} \times \text{STR}, \text{ if } \text{SOC} < \text{SOCmax} \text{ then } \text{STR}=1, \text{ if } \text{SOC} \geq \text{SOCmax} \text{ then } \text{STR} = 0$$

where STR is the soil structure parameter and SOCmax is a defined threshold value, which depends on the interest in SDS source mapping, that is, only desert areas or areas that include surfaces vulnerable to wind erosion under extreme drought and negative human impacts. However, relations between wind erosion impact and SOC content is poorly known, and thresholds should be carefully chosen in order not to exclude potential dust emission areas.

Bare soil surface

The bare soil surface fraction in the grid box can be detected using NDVI (or EVI) values above zero to exclude water bodies, snow and ice cover. Values up to 0.1 fully distinguish bare surfaces, but areas with higher values can also include a fraction of bare soil surface.

The relation of NDVI values with a fraction of vegetation has not yet been determined, but according to the literature (which is mainly related to NDVI rather than EVI for this purpose), the upper boundary of 0.15 can include a major part of fully bare and sparsely vegetated surfaces. Water, snow and vegetation cover may change depending on the SDS source drivers. A regular update of the values of this parameter is recommended. Implementation of data on bare soil surface fraction (BSF) can be done as follows:

$$\text{SOURCE}= \text{FTX} \times \text{STR} \times \text{BSF}, \text{ if } \text{NDVI} > \text{NDVImax} \text{ and } \text{NDVI} \leq 0 \text{ then } \text{BSF}=0, \text{ if } 0<\text{NDVI}\leq 0.1 \text{ BSF}=1, \text{ and if } 0.1 < \text{NDVI} \leq \text{NDVImax} \text{ then } 1 \geq \text{BSF} \geq 0 \text{ or also can be set to BSF}=1$$

where BSF is the bare soil fraction with values from 0 to 1, depending on the NDVI (EVI) values, and NDVImax is the threshold for NDVI. This threshold value may be adjusted to different land cover types.

The relation of BSF and NDVI values, when the soil surface in the grid box is partially covered with vegetation, can be improved with the use of higher-resolution soil surface observations. Due to less noise in the EVI data compared to NDVI, the use of EVI should be considered.

Land cover or land-use data can be used to identify types of SDS sources, by overlaying this information with SOURCE data, and to double check exclusion of irrelevant surfaces. Land cover types that can be potential SDS source areas include bare land, grassland (pastures), cropland, scrubland (open scrubland). These data are updated annually.

Soil moisture

Soil moisture usually depends on the climate zone. However, as soil moisture varies seasonally and is dependent on weather conditions, a process of looking at soil moisture for all areas with possible low soil moisture permits the detection of seasonal and occasional SDS sources. This is particularly true at the beginning of the growing season.

Soil moisture measurements are usually very sparse and/or not available to the public. A few global data sets are available, from the European Centre for Medium-Range Weather Forecast (ECMWF) or National Oceanic and Atmospheric Administration (NOAA) analysis and satellite data. Data are updated every 6 to 12 hours, or daily. Relatively new ERA5-Land database provides data on higher spatial and temporal resolution, generated by surface scheme which is a part of the ECMWF forecast system, with available data at 1 hour interval.

If soil moisture (SM) is below a certain threshold, emission is possible:

$$\text{SOURCE}= \text{FTX} \times \text{STR} \times \text{BSF} \times \text{DSF}, \text{ if } \text{SM} \leq \text{SMmax} \text{ than } \text{DSF} = 1, \text{ if } \text{SM} > \text{SMmax} \text{ DSF} = 0$$

where DSF is dryness of soil surface and permits SDS source activity if SM is below threshold SMmax.

Determining a threshold is not easy for two reasons:

1. Water capacity is different for different soil compositions.
2. Moisture thresholds where emission stops can change with wind velocity (higher value where there is higher wind velocity).

Adjusting SMmax can be done using information on drought, aridity, national data on soil types and their characteristics and values of SM that coincide with dry periods.

Frozen soil

Soil temperature (ST) is important for excluding frozen soil surface areas. This is especially important during winter and early spring seasons, when areas are without vegetation and strong winds are possible (usually in continental climates). Temperature thresholds for frozen soil are below -10°C in case of lower soil moisture and depend on soil composition. If the soil moisture is higher soil freezing temperature is increasing.

Temperature data can be derived as soil moisture data, from EMWF or NOAA reanalysis and satellite data, and are also updated in 6 to 12-hour cycles, or daily. It can be obtained from ERA5-Land database on higher spatial and temporal resolution. If soil temperature (surface air temperature can also be used) is above some threshold value, emission is possible:

SOURCE= FTX x STR x BSF x DSF x NFS , if ST ≥ STmin than NFS = 1, if ST < STmin NFS = 0

where NFS is not a frozen soil surface and permits SDS source activity if ST is above threshold STmin. Issues related to determining this threshold are similar to those of SMmax but related to conditions favourable for soil freezing.

8.6.3. Data sources for sand and dust storm source calculations

The data sets described as follows can be used for SDS source mapping. The data sets are geo-referenced, in standard grid presentations and regularly distributed globally. However, a user should investigate possible sources of relevant data for their region which can improve SDS source mapping accuracy.

Soil texture (clay and silt content) and SOC data:

The International Soil Reference and Information Centre (ISRIC) world soil information database provides SoilGrids (soil global gridded information) which enables users to manipulate data online and to download data sets (Hengl et al., 2014; Hengl et al., 2017). Data sets are 1km resolution and higher, available in TIFF format and in WGS84 latitude-longitude projection. Another extensive source on soil data are FAO databases. The relevant links are:

- http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/
- http://www.isric.org
- https://soilgrids.org
- https://www.isric.org/explore/soilgrids
- https://files.isric.org/soilgrids/

Bare surface and land cover data:

NDVI and EVI data are Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua products. The global MOD13A3 data set is recommended, as it is updated every month and has been available since the year 2000, in 1km resolution in Sinusoidal projection. A more frequent 16-day product, available in higher resolution, is MOD13A2. The file format is HDF-EOS. The relevant links are:

- https://modis.gsfc.nasa.gov/about/
- https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD13A3/
- https://e4ftl01.cr.usgs.gov/

The recommended MODIS Land Cover Type product is MCD12Q1 Version 6 (variable LC-Type1 – IGBP classification scheme for land cover). It is updated annually and has been available since 2001 in 500m resolution in Sinusoidal projection. The file format is HDF-EOS. The relevant links are:

- https://lpdaac.usgs.gov/products/mcd12q1v006/
- https://e4ftl01.cr.usgs.gov/MOTA/MCD12Q1.006/

One tool that can be used for decoding the MODIS data and for data manipulation is R studio, with the following libraries: MODISTools, raster, gdal and gdalUtils." R studio may be commercial software (see https://www.rstudio.com/).

More information about NASA products and Earth data can be found here:

- https://earthdata.nasa.gov .

Another option for land cover data are provided by the European Space Agency Climate Change Initiative (ESA CCI) (Wei et al., 2018). Data sets are annual, available for the period 1992–2015, with a resolution of 300m. The file types are GeoTIFF and NetCDF. Registration is required to download data. The relevant links are:

- http://www.esa-landcover-cci.org
- http://maps.elie.ucl.ac.be/CCI/viewer/index.php

Soil moisture and temperature data:

For soil surface moisture and temperature data, it is recommended to use data sets from the European Centre for Medium-Range Weather Forecast ERA5 product, available for public use. Data are in 30km (0.25° x 0.25°) resolution, featuring hourly and monthly averages since 1979. Data projection is WGS84 latitude-longitude and the file format is GRIB. The decoding software is wgrib. Soil data are available for four depths. The relevant link is:

- https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

Another global reanalysis product is the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 Project, which provides data sets in much coarser resolution. Data is for the period from 1948, at 2.5°x2.5° resolution, with a 6-hour temporal resolution and daily averages (Kalnay et al. 1996). The file format is netCDF and the decoding software is NCL, Python and Fortran.

Soil moisture data is also available from the ESA CCI: ESA CCI SM version 04.2 ESA – CCI Surface Soil Moisture merged with the ACTIVE Product. Data sets are daily (reference time 00 UTC), in 0.25°x0.25° resolution, with two versions covering the period 1978 to 2016. The relevant link is:

- https://www.esa-soilmoisture-cci.org

Soil moisture and temperature data are available on higher spatial (0.1o) and temporal resolution (1h) in ERA5-Land database:

- https://www.ecmwf.int/en/era5-land

All data should be adjusted to the same projection, resolution and grid position for easy data manipulation.

8.6.4. Use of topographic data for sand and dust storm source mapping

Data on soil characteristics in global data sets are constantly improving. However, the quality of these data is likely inadequate for most parts of the world. This is due to the high spatial variability of soil composition, the limited areas sampled compared with the total Earth land surface and the lack of international data exchange. The most reliable parameter is soil texture. To further distinguish areas with finer particles from coarser topsoil, information on topography can be used.

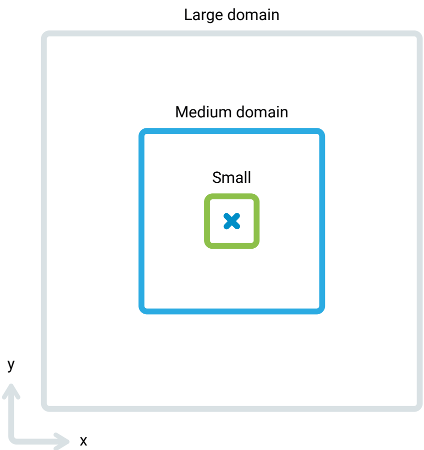
Under the assumption that alluvial deposits of fine soil particles are dominant in areas of dried river- and lake beds, and retreating glaciers, that is, in places exposed to increased erosion during the topsoil formation, SDS source mapping can be improved. Such areas are placed in topographical lows (pits), which can be derived from data on topography. Topographical lows can have large scales (such as the Taklamakan desert) due to very small areas – "hotspots" (for example, Iceland sources).

The simple approach described in Ginoux et al. (2001) and used for global dust forecast purposes in Kim et al. (2013) can be used to detect topographical lows. The function they used to estimate the fraction of alluvium available for wind erosion, at a point, scaled to values from 0 to 1 (lower values mean a low alluvium fraction is available, and higher values mean higher alluvium content), is now recognized as S-function. The S-function is calculated using maximum, minimum and in point altitudes, searching the values within the box 10°x10° around the point for which S is calculated. Simple modification of this approach is possible to include smaller-scale features (hotspots).

Figure 27 presents several domains for calculation of the value of the S-function in the middle (blue x). Applying this calculation in high-resolution and with different domains, large- and small-scale features of topographical lows can be recognized.

Figure 28 presents a vertical cross section of areas that S-function values recognize as topographical lows (pits), indicating the calculation of the S value for different domains (arrows). If high S values are recognized in all domains for the point (grid box) where the S-function is calculated, it is highly probable that the grid box is an SDS source hotspot, if allowed by other soil surface parameters. If values obtained for smaller domains have low values, it means that a large region is flat and most probably much less SDS-productive, but individual SDS source hotspots are possible.

Figure 27. Different size domains for calculation of S-function



Source: Ginoux et al., 2001.

Figure 28. Areas (arrows) indicate different domains identified as topographical lows

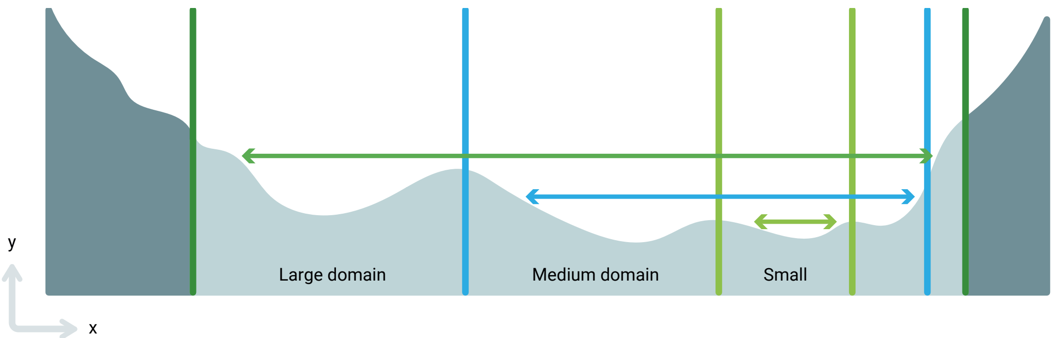


Figure 29 provides an example of a global calculation of the average S-function at 0.0083° resolution (30 arcsec, about 1km on the equator) using an ensemble of values obtained for four different size domains (10°x10°, 5°x5°, 2.5°x2.5°, 1.25°x1.25°). Values are obtained as the average of S-function results for different domains.

From the assumption based on S-function meaning, lower values contain a lower fraction of alluvium (which is considered SDS productive), and higher values most probably contain a higher content of SDS productive soils. Improving the identification of hotspots associated with alluvial deposits – which are of smaller spatial scale – is done by giving greater weight to results of S-function calculations using smaller domains or using higher-resolution topography data with a smaller domain for S-function calculation.
To identify the most SDS-productive regions globally, identification of bigger pits is improved by giving greater weight to results of S-function calculations obtained with a larger domain. However, this results in a loss of fine high-resolution spatial source identification. The results of this process coincide with global SDS-productive regions (Ginoux et al., 2001). Note that **Figure 29** is an additional component for SDS source mapping and is not a map of SDS sources itself. S-function values are sensitive to i) the domain chosen for the calculation and ii) the resolution of topographic data.

Adding this kind of information to an SDS source map can help to distinguish more SDS-productive areas and exclude less significant areas:

PSOURCE = PSF x SOURCE

where PSF is preferential SDS-productive surface, with values 0 to 1. It can be derived using the approach provided by Ginoux et al. (2001) from an ensemble of S-function values derived for different domains. It is possible to obtain ensemble values that give more weight to the small-scale features, but that also provide information on larger impact areas, which may prove useful. Another way for using information obtained from S-function is to apply some adjustments (corrections) of soil texture data to enhance the content of fine soil particles content in areas where higher probability for higher alluvium content (higher S-function values).

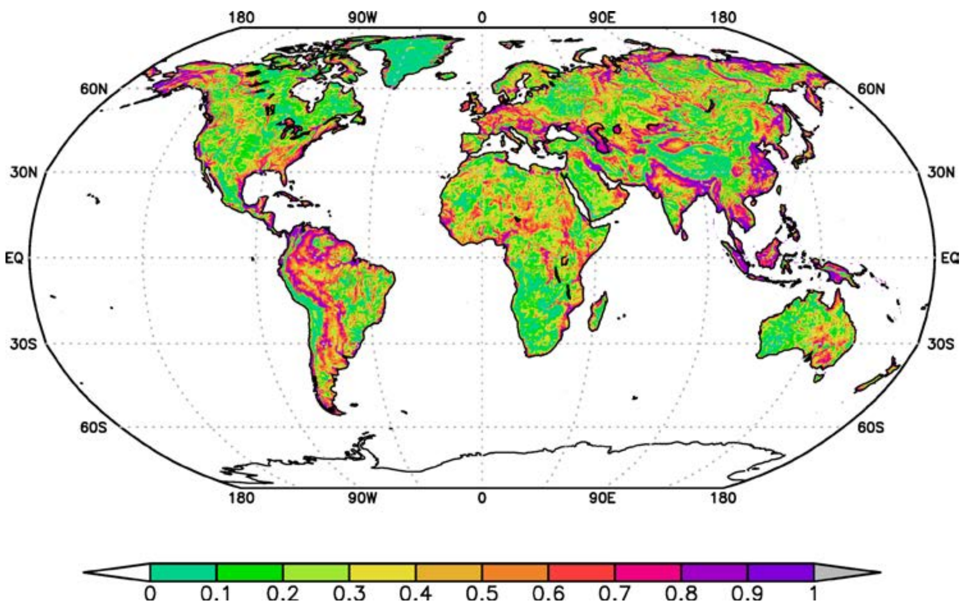


Figure 29. Average S-function values from four different domains (10°x10°, 5°x5°, 2.5°x2.5°, 1.25°x1.25°) on 0.0083° (30 arcsec) resolution, using topography data of the same resolution

Source: Ana Vukovic and Bojan Cvetkovic.

Besides using topographic data to distinguish more productive areas, other data sets may be employed (Zender et al., 2003). Geomorphology data sets may provide information regarding the location of alluvium (Bullard et al., 2011; Iwahashi et al., 2018), and PFS can be derived from such information.

Another example for implementation of topographic data in SDS source mapping is using watershed flow accumulation data (Feuerstein and Schepanski, 2019). If possible, monitoring and implementation of very high-resolution topographic data and local surface roughness using remote-sensing techniques may provide additional information for SDS source monitoring and higher-quality SDS source mapping (Menut et al., 2013; Yun et al., 2015; Demura et al., 2016; Kim 2017; Lin et al., 2018).

8.7. Conclusions

Choosing the methodology for SDS source mapping requires having a clear purpose for which the SDS source map will serve. If the purpose of the SDS source map is to estimate global distribution of major and most active global (or continental) SDS sources, without the need for a relatively precisely defined spatial pattern of most SDS-productive hotspots, mapping can be done using observations on SDS occurrence. This will serve to better understand aspects such as the global airborne dust cycle, regional dust transport and the seasonality of major sources.

If the purpose of SDS source mapping is to estimate the potential of soil surfaces to produce SDS in favourable weather conditions, a more complex cluster of data is required, as explained in the methodology for high-resolution SDS source mapping.

This approach enables a spatial SDS source pattern to be distinguished at high resolution, including most critical hotspots. This approach is recommended for vulnerability and risk assessments, especially for local SDS events, which are usually not very visible in SDS observations, as well as for planning SDS source mitigation and improving warning and alert systems.

Understanding the spatial and temporal variability of soil surface conditions and activity of SDS source areas depends on many factors. However, the use of national data sets and field observations can significantly increase the accuracy of SDS source mapping.

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9. Sand and dust storm forecasting and modelling

Chapter overview

This chapter covers the concept of impact-based, people-centred forecasting and summarizes the procedures used in the approach. The chapter includes an extensive discussion of the technologies and infrastructure used to collect data on sand and dust storms (SDS), including in situ and remote sensing options. An extensive discussion is provided on the global World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS), with an example of how this system can be linked to national-level forecasting. Information is provided on national-level SDS data collections, including on national meteorological and hydrometeorological services, private weather services and citizen science engagement in SDS.

This chapter is based on the experience of the WMO SDS-WAS and national SDS forecasting systems and also addresses SDS modelling. It should be read in conjunction with **chapter 10** on SDS early warning, as well as **chapter 2**, which provides an overview of SDS.

9.1 Impact-based, people-centred SDS forecasting

Impact-based forecasting provides information on the impacts of forecasted weather on the individuals who will experience it (i.e. people-oriented). Impact-based forecasts are provided to disaster management, health, transport and other stakeholders and also, importantly, to the public, through impact-based forecasting and warning services (IBFWS).
The outreach to the public recognizes that those individuals who can be affected by forecasted weather have the first, and often best, opportunities to mitigate or avoid the impact of this weather (see **chapter 10** on SDS early warning). Impact-based forecasts are therefore intentionally people-centred (see **Box 13**).

Impact-based (people-centred) forecasting is an integral part of the SDS warning process. This chapter focuses on forecasting and public outreach elements of the SDS forecasting process. **Chapter 10** focuses on the warning process and provides an overview of the combined forecast and warning process.

Box 13. Comparing traditional and impact-based people-centred forecasts

A traditional SDS weather forecast can state that sand and dust conditions are expected during a certain period over a general area, for example: *There will be a dust storm in the next few days affecting the country*.

An impact-based forecast is more precise, for example: *There will be a high-intensity dust storm over the next two days affecting the four northern states of the country. The storm will pose difficulties for individuals with breathing problems. These individuals should take steps to protect against the dust, including staying inside and using air conditioners where possible. Schools may also limit outside time for students to reduce the impact of the dust*.

In other words, impact-based, people-centred SDS forecasting:

- focuses on the impacts of an SDS event on specific groups, based on SDS type and level of risk
- indicates the locations that will be affected
- indicates the expected duration of the impacts of the SDS event and
- provides information to reduce the impacts of the SDS event

9.2 Components of impact-based forecast and warning

Impact-based forecast and warning services are based on:

- A very good, near real-time understanding of evolving weather conditions, based on weather models incorporating accurate and timely weather data from ground, ocean and space-based observing systems.
- A clear classification of weather hazard categories that affect a particular location and their corresponding types and levels of impact.
- A risk assessment matrix developed through consultations between a national meteorological and hydrological service (NMHS) and stakeholders (for example, national disaster management authority and the transport and education sectors). The risk matrix enables a forecaster to assign a level of impact for specific locations and on specific groups and assets when issuing an impact-based forecast.

The risk assessment structure used in impact-based forecasting "is defined as the probability and magnitude of harm attendant on human beings, and their livelihoods and assets because of their exposure and vulnerability to a hazard. The magnitude of harm may change due to response actions to either reduce exposure during the course of the event or reduce vulnerability to relevant hazard types in general" (World Meteorological Organization [WMO], 2015). This definition is sufficiently close to the definition used in **chapters 5** and **7**, meaning that information collected through the risk assessment and vulnerability procedures throughout those chapters can be used to support impact-based forecasting.

WMO sets out a mathematical formula to calculate impact risk. The formula incorporates the uncertainty associated with forecasts (WMO, 2015). Uncertainty is able to be included because predictive models include information on expected accuracy.

In practice, mathematical calculations of impact risk may not always be practical. Most often, this is due to a lack of sufficient or appropriate data on exposure and vulnerability. In these cases, the forecaster, in consultation with other experts, would need to make the best-fit assessment of the impacts of an SDS event and incorporate any caveats on the forecast into the formal forecast statement.

Three decision-making procedures can contribute to an impact-based forecasting approach (WMO, 2015):

- The forecaster would provide a simple link between the nature (such as intensity, duration, location) of the SDS event and its expected impacts. For instance, if a dense area of dust was identified as approaching a city, the forecast would reflect that the dust would be dense. The forecast would not describe the impact of this dense dust on vulnerable groups or services (for example, transport) in the city. It would be expected that, on learning of the forecast, people would take the necessary action based on previous experience or advice from others.
- The forecaster uses their experience, based on past SDS events and information on the forecast event, to identify likely impacts. For instance, with the SDS approaching a city, the forecast would indicate the expected time of arrival and state that people with health problems may be affected and should stay indoors, thus addressing a common SDS impact and providing relevant advice. While impacts would be identified, they would not be highly specific and only a general mention of measures to reduce impacts would be made.

- The forecaster would draw directly from models setting out likely (uncertainty-defined) magnitudes of the SDS event as well as risk assessments and would identify:

    - who, specifically, could be impacted
    - how, specifically, they would be impacted and
    - where, specifically, these impacts would take place

The resulting forecast would:

- include more specific information on impacts on vulnerable groups (for example, older persons, children)
- be more precise about when the SDS event was expected to arrive and end
- indicate if some locations may be more or less impacted
- identify how the SDS event could affect services and commercial and other activities, such as delaying air travel and slowing traffic during rush hour

Clearly, the third, model-driven, approach is the most complicated. It is based on good models (or ensembles of models), an understanding of who and where could be impacted based on risk and vulnerability assessments, and what these impacts could be over time. Developing this depth of knowledge about SDS requires an NMHS to work in partnership with other sectors to develop a comprehensive understanding of SDS and their diverse impacts (WMO, 2015; WMO, 2020).

The second process, which relies less on modelling and more on experience, can be effective if technical means are limited. The forecaster's use of their experience to identify impacts can be strengthened by:

- Using a consensus-approach to identify impacts, where several forecasters agree as to expected impacts.
- Incorporating input from stakeholders, including the national disaster management authority, on impacts and at-risk groups. This can be done through the risk assessment methods set out in **chapters 5** and **7**, as well as consultations with key sectors that are affected by SDS (for example, health, education, disaster management offices). (**Box 17** in **chapter 10** identifies SDS early warning stakeholders, which overlap with forecast stakeholders.)

The consultations can use a retrospective approach, whereby the NMHS collects impacts from stakeholders following an SDS event and accumulates a list of types of events linked to specific impacts over time. This event-to-impact information can be used to develop a reference table which can be incorporated into the forecast process. A process to collect information on past SDS is provided in **chapter 5**.

The process of establishing impact-based forecasting involves developing standard criteria for classifying different levels of SDS events. The SDS hazard typology in **chapter 4.2.5** provides a general grouping of SDS events into similar categories. However, more detailed classifications, based on standard criteria to define the meteorological magnitude of a specific SDS, are useful for the impact-based forecasting process.

An example for a haboob would be setting standard criteria for different magnitudes of a haboob based on wind speed, dust content, presence or absence of precipitation after the passage of a haboob, and so on. These characteristics are then grouped to identify haboobs of different intensities, such as class one, class two, class three, class four. These groupings, or classes, of haboobs are then linked to anticipated impacts based on impacts during past haboobs. For instance, a class two haboob would cause changes in aircraft landing patterns, while a class three haboob would close an airport to all landings and take-offs. (**Chapter 4** describes a preliminary typology for SDS which uses a similar approach.)

While the process of defining and assigning impacts may seem complicated, the link between an SDS event of a specific intensity and its expected impacts on humans and society must be understood if the forecasting process is to work. Similar classification systems are used for cyclones, hurricanes and typhoons.

In developing impact-based forecasts, it is also necessary to revisit the issue of who has the authority to issue warnings (see **chapter 10**). While an NMHS may develop impact-based forecast procedures (including criteria and standards for classifying SDS) and can generate forecasts which specify impact and measures to address this impact, the authority to release this information may not rest with the NMHS.

The actual difference between a prognostic forecast of weather conditions and an impact-based forecast may not be that great, but prognostic forecast would be considered the regular and routine work of the NMHS. Moving into identifying impact and steps to take to address this impact may move an NMHS into a new area of work and responsibilities.

WMO suggests that this shift is necessary to ensure weather information reduces negative impacts (WMO, 2015), but this process needs to be coordinated with other stakeholders. **Chapter 5** in **WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services** provides a road map for how impact-based forecasting can be integrated into the work of an NMHS and its partners (WMO, 2015).

9.3 SDS information collection and forecast technology and infrastructure

9.3.1. Overview

This section reviews the technology and physical infrastructure that collects and processes information on SDS in support of forecasting and warning. This infrastructure ranges from ground stations to satellites and incorporates model-based and other analysis to deliver information which can be used to provide an impact-based warning to those who may be affected by an SDS event.

Observations of dust transport and concentrations in the atmosphere are very important to early warning and risk reduction in many sectors, including health, transport, education and industry. There are two approaches to collecting information on sand and dust:

- In situ data from synoptic or aeronautical meteorological stations providing information on horizontal visibility, dust particulate concentration (for example, PM_{10}) and weather at the time of the report. These reports can be near real-time from automatic weather stations or several times a day from human reports.
- Remotely sensed, including ground- and space-based instruments, with data often collected on a near real-time basis, although processing may be completed at regular intervals, for instance, every six or 12 hours.

In situ measurements of particulate matter concentration are systematic and have high spatial density in developed countries. However, they can be very sparse, discontinuous and rarely near real-time close to the main global sources of dust.

Satellite products present global coverage. However, they usually integrate the bulk aerosol content over the vertical column and do not provide information close to the ground.

9.3.2. In situ: visibility information from weather reports

Where weather records have excellent spatial and temporal coverage, visibility data included in meteorological observations can be used as an alternative way of monitoring dust events. Visibility is mainly affected by the presence of aerosol and water in the atmosphere.

The use of visibility data has to be complemented with information on present weather to discard those cases where visibility is reduced by the presence of hydrometeors (such as fog or rain) or particles of a different nature (such as smoke, ash or anthropic pollution).

Table 20 shows the WMO synoptic codes of present weather that can be associated with airborne sand and dust (Secretariat of the World Meteorological Organization, 1975).[1]

Table 20. WMO synoptic codes associated with airborne sand and dust

Description	WMO code	Associated with sand and dust
Haze	05	Unclear
Widespread dust in suspension not raised by wind	06	Yes
Dust or sand raised by wind	07	Yes
Well-developed dust or sand whirls	08	Yes
Dust or sandstorm within sight but not at station	09	Yes
Slight to moderate dust storm, decreasing in intensity	30	Yes
Slight to moderate dust storm, no change	31	Yes
Slight to moderate dust storm, increasing in intensity	32	Yes
Severe dust storm, decreasing in intensity	33	Yes
Severe dust storm, no change	34	Yes
Severe dust storm, increasing in intensity	35	Yes
Heavy thunderstorm with dust storm	98	Yes

Human weather observations are made on a fixed schedule and, in some locations, without a full (360 degree) view of the sky. In general, the start and end times of weather events (including SDS events) are also recorded at, and reported by, meteorological observatories.

However, the WMO coding may not indicate that an SDS event has occurred if the event takes place between reporting times or does not take place within the viewing area of an observation station. See O'Loingsigh et al. (2014) on weather station data and identifying SDS events.

Horizontal visibility is an indication of the intensity of attenuation of solar radiation by the suspended particles including dust. Several empirical equations relating to surface dust concentrations and visibility have been proposed. However, there is not a universal relationship between both magnitudes, as visibility reduction is strongly influenced by particle size distribution and has a clear dependence on ambient humidity. In turn, size distribution can be highly variable depending on source soil characteristics, wind erosivity and the observation point's distance from the eroding source.

1 The WMO definitions are also available at https://cloudatlas.wmo.int/lithometeors-other-than-clouds.html, with pictures for reference.

Empirical calculations relating to surface dust concentrations and visibility include:

- North America: Chepil and Woodruff (1957), Patterson and Gillette (1977)
- West Africa: D'Almeida (1986), Mohamed et al. (1992), Camino et al. (2015)
- North-East Asia: Shao et al. (2003)
- East Asia: Wang et al. (2008)
- West Asia: Dayan et al. (2008)
- North-East Asia: Jugder et al. (2014)
- Australia: Baddock et al. (2014)

9.3.3. In situ: air quality monitoring stations

Air quality monitoring stations regularly collect data on the presence of particulate matter in the sampled air. This matter can include mineral dust from SDS events, as well as background levels of airborne particles from, for instance, industrial pollution or mining.
Various international and regional organizations and national governments have established guidelines, recommendations, directives or legislation on the maximum permissible concentration levels of atmospheric constituents considered as pollutants. None of these regulations specifically refer to mineral dust.

The main air quality limits are associated with World Health Organization (WHO) guidelines on air quality related to human health. Presently, only PM_{10}, $PM_{2.5}$ and PM_1 are considered, as these variables are the references for the epidemiological studies. There is no evidence about how the chemical composition of aerosols and specifically sand or dust can affect human health.

At the same time, regulations have been set for concentrations of suspended particles in the air, including:

- The European Union 2008/50/EC Directive (European Commission, 2008) sets 50 μg/m^3 as the 24-hour-mean limit value for PM_{10}, with 35 μg/m^3 permitted. The WHO guidelines for particulate matter exceedances each year set 40 μg/m^3 as the annual-mean limit value for PM_{10}, compared with 25 μg/m^3 for $PM_{2.5}$.

- Guidance on ozone, nitrogen dioxide and sulphur dioxide to reduce the health impacts of air pollution recommends a maximum 24-hour-mean value of 50 μg/m^3 and an annual-mean value of 20 μg/m^3 for particles with aerodynamical diameter less than 10 μm (PM_{10}), with a maximum 24-hour-mean value of 10 μg/m^3 and an annual-mean value of 25 μg/m^3 for $PM_{2.5}$ (European Commission, 2008).

- The United States of America National Ambient Air Quality Standards (https://www.epa.gov/criteria-air-pollutants/naaqs-table) set 150 µg/m³ as the 24-hour-mean limit value for PM_{10}, not to be exceeded more than once per year on average over three years. They also set an annual-mean limit value (averaged over three years) of 12 µg/m³ for $PM_{2.5}$ and a 24-hour-mean (ninety-eighth percentile, averaged over three years) limit value of 35 µg/m3 for $PM_{2.5}$.

Based on these guidelines and standards, air quality measurement stations usually assess total suspended particle (TSP) levels at PM_{10} or $PM_{2.5}$ concentrations. These measurements integrate the contribution of the various elements in the air and are not exclusively characteristic of dust particles. They are, however, very useful for monitoring mineral dust events because of the episodic nature of SDS events.

It is important to understand how the location of a measurement station may affect data on TSP or PMx levels. For example, an abundance of anthropogenic particulates close to cities, large industrial parks or roads can mask the presence of mineral dust. On the other hand, bulk aerosol mass measurements from stations that usually record a low aerosol background and are sited in places where it is known that high aerosol mass events are caused by dust episodes represent a relatively cheap approximate method for long-term dust observation.

Gravimetry (weighing) of sampling filters is the reference method used to measure the concentration of particulate matter. The ambient air is passed through a filter, where particles are collected. Filters are weighted before and after sampling at a controlled temperature and relative humidity.

Mass concentrations are determined by dividing the increase in the filter mass (due to sample collection) by the volume of sampled air.

Reference gravimetric methods used in air quality networks (for example, DIN EN 12341:2014, Ambient air – Standard gravimetric measurement method for the determination of the PM_{10} or $PM_{2.5}$ mass concentration of suspended particulate matter,[2] or its United States of America equivalent) facilitate data comparability between different stations.

However, filter-based sampling is labour intensive. Filters must be conditioned, weighed before sampling, installed and removed from the instrument, and reconditioned and weighed again at a special facility. Results may not be available for days or weeks. Furthermore, filter-based techniques integrate samples over a long period of time, usually 24 hours, to obtain the required minimum mass for analysis.

With the increasing concerns about the effect of particulate matter (PM) on human health, the limitations of the time-integrated filter approach are becoming apparent, while the delay involved in sampling and determining PM concentration is also a concern.

Continuously operating sampling methods such as tapered element oscillating microbalance (TEOM) or beta attenuation monitoring can detect suspended matter almost in situ, but these methods require operating conditions that differ from the environmental situation or are not completely specific to mass. It is, therefore, necessary to introduce correction factors in these measurements.

In TEOM devices, the mass of the particles collected on a substrate that vibrates at constant amplitude is determined as a function of the decreasing frequency prompted by an increase in particle

2 Available for purchase at https://shop.bsigroup.com/ProductDetail?pid=000000000030260964.

mass through time. Alternatively, in the beat-attenuation devices, the number of beta particles transmitted across a filter decreases when the sample load increases.

Figure 30 shows the monthly record of PM_{10} and $PM_{2.5}$ from the TEOM station set in Granadilla, Canary Islands, Spain. Three dust episodes can be clearly identified as the peaks of mass concentration for PM_{10}.

Chemical analysis is required to determine the proportion of mineral dust present in filter samples. The most common method is based on determining the mean content of selected tracers present in soil. Silicon (Si) and aluminium (Al) account respectively for 33 per cent and 8 per cent of mean soil composition.

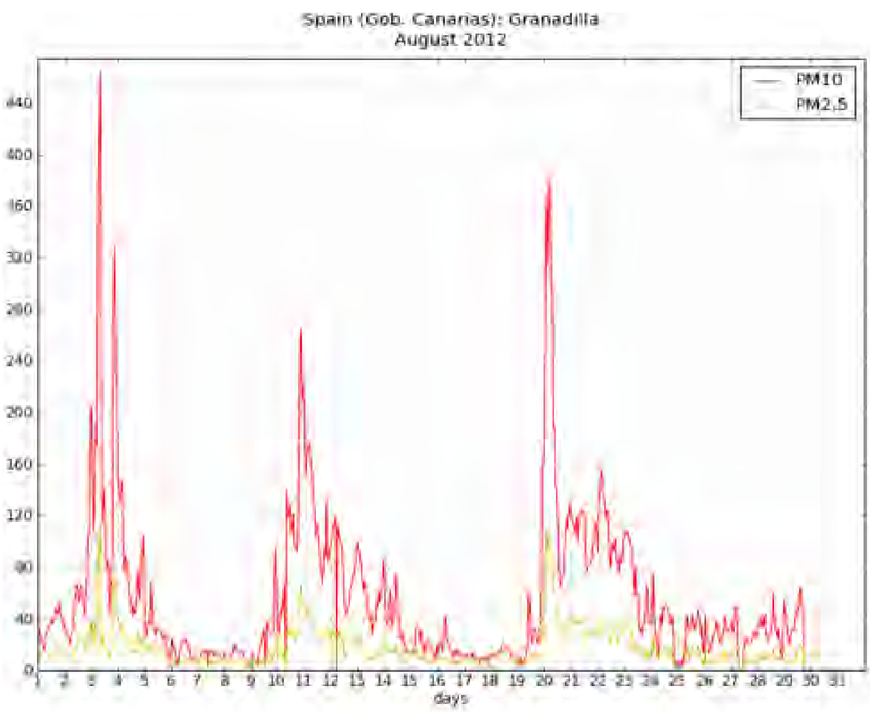


Figure 30. The PM_{10} and $PM_{2.5}$ records from Granadilla, Canary Islands, Spain for August 2012 with Saharan dust outbreaks indicated in peak values

Source: Gobierno de Canarias [Data provided by the Government of the Canary Islands].

Detailed information on the methods used for dust monitoring and characterization (including size distribution, bulk composition and optical properties) can be found in the review paper by Rodríguez et al. (2012) and references therein. As a synthesis, tracer analysis is the most accurate procedure, but the filter ash method is a less expensive alternative.

Air quality networks performing systematic measurements with high spatial density are well established in developed countries. However, these measurements can be very sparse, discontinuous and rarely near real-time close to the main dust source areas. Furthermore, there is no protocol for routine international exchange of air quality data, so their use is often limited to the national level.

The WMO Global Atmosphere Watch (GAW) Programme[3] is working to cover this gap. Its main goals are to “ensure long-term measurements in order to detect trends in global distributions of chemical constituents in air and the reasons for them.

3 See https://community.wmo.int/activity-areas/gaw

With respect to aerosols, the objective of GAW is to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal timescales and on regional, hemispheric and global spatial scales" (Global Atmosphere Watch, World Data Centre for Aerosols, n.d.).

The GAW Programme envisions the comprehensive, integrated and sustained observation of aerosols on a global scale through a consortium of existing research aerosol networks that complement aircraft, satellite and environmental agency networks (WMO, 2009). According to GAWSIS,[4] the GAW aerosol network consists of 28 global stations and over 200 fully operational regional and contributing stations.

9.3.4. Remotely sensed: satellite-derived red-green-blue (RGB) dust products

Satellite products offer large spatial coverage (regional to global) and regular observations and are available to weather centres and other institutions in near real-time. However, using satellite products to monitor dust events faces several problems:

- The high integration of satellite products over the atmospheric column makes it difficult to ascertain the elevation of dust particles, i.e. whether they are close to the ground or at altitude.
- Low aerosol detectability over bright surfaces, such as deserts, affects instruments operating in the visible or near-infrared part of the spectrum. In addition, products from these spectral bands are not available at night.
- The high-resolution instruments flying on board polar-orbiting satellite platforms have the potential to provide good quality dust information, but this information is not frequent enough for SDS forecasting.
- There is no information about dust layers under clouds.

Operational meteorologists typically use multi-spectral product measurements by instruments on geostationary satellites for dust monitoring and nowcasting. The latest generation of geostationary satellites are a vital tool for atmospheric monitoring, since they combine the specific advantages of geosynchronous orbits (high-frequency coverage over a vast geographic domain) with the capabilities of high-resolution radiometers.

Multi-spectral products are based on several monochrome images of the same view that are captured by different sensors. By providing extra information that highlights specific features that are not perceptible in the original images, these products make it easier to detect and track dust clouds.

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) RGB-dust product is part of a collection referred to as "RGB imagery" or "RGB products", which are implemented to address several forecasting challenges for both daytime and night-time applications. In these products, brightness temperatures or paired band differences are used to set the red, green and blue intensities of each pixel in the final image, resulting in a false-colour composite (European Organisation for the Exploitation of Meteorological Satellites [EUMETSAT], 2009).

The EUMETSAT Meteosat Second Generation (MSG) dust product is based upon three infrared channels of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the MSG satellite.

It is designed to monitor the evolution of dust storms over deserts during both day and night.

4 See https://gawsis.meteoswiss.ch/GAWSIS/#/

The RGB combination exploits the difference in emissivity between desert surfaces and dust.

In addition, during the daytime, the RGB combination exploits the temperature difference between the hot desert surface and the cooler dust cloud (**Figure 31**). Dust appears pink or magenta in this RGB combination. Dry land appears from pale blue (daytime) to pale green (night-time). Thick, high-level clouds have red-brown tones while thin, high-level clouds appear very dark (almost black).

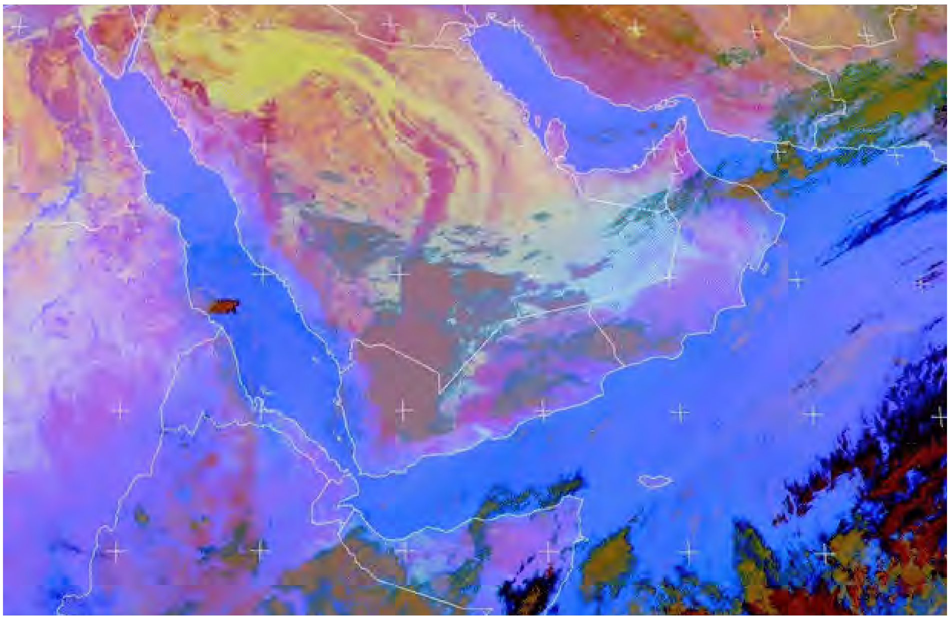
Emissions and subsequent transport in individual dust events can be very well observed and followed in the RGB composite pictures, especially using temporal loops. The full disc view includes the whole of Europe, all of Africa and the Middle East and allows frequent sampling (every 15 minutes) with a spatial resolution of 3 km in the nadir. This enables rapidly evolving events to be monitored, which in turn helps the weather forecaster swiftly recognize and predict hazardous dust events.

The RGB-dust product has some important limitations. Firstly, high cloud cover can obscure dust plumes beneath clouds and make spatial analysis of the dust more difficult. Secondly, the magenta/pink variations are not indicators of dust thickness.

Finally, the product provides little or no information on the height of the dust cloud. In particular, it is almost impossible to determine from the images whether there is substantial dust concentration near the ground surface.

More recently, similar products have been developed for other platforms. The Japanese Himawari-8/Advanced Himawari Imager (AHI) allows forecasters to use an RGB-dust product to monitor airborne dust over the Western Pacific region. In 2016, EUMETSAT relocated Meteosat-8, the first of the MSG satellites, to 41.5°E to enable data coverage of the Indian Ocean to continue. It allows the EUMETSAT RGB-dust product to be generated for West Asia, a region where the coverage was deficient.

Figure 31. EUMETSAT RGB-dust product for West Asia on 20 December 2019



Source: Image provided by EUMETSAT.

An RGB-dust product has been made available from the Advanced Baseline Imager (ABI) instrument on board GOES-16 to monitor dust events over America and its surrounding oceans. GOES-16 is the first spacecraft in the National Oceanic and Atmospheric Administration's (NOAA) new generation of geostationary satellites. As part of NOAA's efforts to prepare users for the new geostationary era, RGB-dust products for America have been under development since 2011, with images from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) instruments.

9.4 The global World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System

9.4.1. Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS)

The earliest prototype of the WMO SDS-WAS was the SDS RDP (Sand and Dust Storm Research and Development Project), which was established in 2004 in Beijing under the framework of the WMO World Weather Research Programme (WWRP) and its GAW Programme (WMO, 2012, 2014; Nickovic et al., 2015). At the third International Conference for Early Warning held in Bonn in 2006, WMO proposed the establishment of an SDS early warning system. In 2007, an SDS-WAS kick-off meeting was held in Barcelona and the fifteenth World Meteorological Congress endorsed the launch of the WMO SDS-WAS.

This system is tasked with enhancing countries' ability to deliver timely and quality SDS forecasts, observations, information and knowledge to users through an international partnership of research and operational communities (Nickovic et al., 2015; Terradellas et al., 2015; Basart et al., 2019; WMO, 2020).

The WMO SDS-WAS works as an international hub of research, operational centres and end users, which is currently organized through three regional nodes:

- a regional node for Northern Africa, the Middle East and Europe (NAMEE), coordinated by a regional centre in Barcelona, Spain, hosted by the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Center (BSC)
- a regional node for Asia, coordinated by a regional centre in Beijing, China, hosted by the China Meteorological Administration
- a regional node for Pan America, coordinated by a regional centre in Bridgetown, Barbados, hosted by the Caribbean Institute for Meteorology and Hydrology

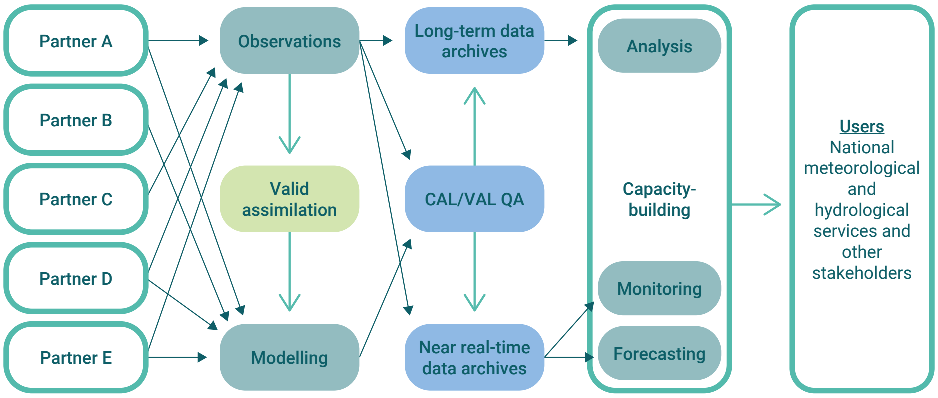
These three regional WMO SDS-WAS nodes are described in more detail in the following sections.

The conceptual operation of an WMO SDS-WAS node is summarized in **Figure 32**. Each WMO SDS-WAS node shares observations and, in some cases, modelling input with partner organizations. A quality assurance control and standardization procedure (i.e. calibration and validation) is applied to produce long-term and near real-time data from observations, followed by dust forecasts. The results are used to analyse, monitor and forecast SDS. These outputs are provided to the NMHS and other stakeholders on a daily basis.

Note that the WMO SDS-WAS centres operate in support of the NMHS, providing them with the best available analysis and forecasts. In turn, each NMHS is responsible for issuing specific forecasts within their respective countries. WMO SDS-WAS products are also available on the respective WMO SDS-WAS centre websites.

Source: Adapted from WMO, 2012.

Figure 32. WMO SDS-WAS regional node operation concept



9.4.2. WMO SDS-WAS regional centre for Northern Africa, the Middle East and Europe

The WMO SDS-WAS regional centre for NAMEE based in Barcelona collects and distributes forecast products based on different numerical models on a daily basis through its web page.[5] In addition to specialists in observations and modelling, the node also has geographers, social scientists and communication experts. This initiative has grown significantly with the incorporation of more and more partners.

At present, 12 modelling groups provide forecasts every three hours of dust surface concentration (DSC) and dust optical depth (DOD) at 550 nm for a reference area extending from 25°W to 60°E in longitude and from 0° to 65°N in latitude.

The reference area is intended to cover the main source areas in Northern Africa and West Asia, as well as the main transport routes and deposition zones from the equator to the Scandinavian Peninsula.

Forecasts of up to 72 hours are updated every three hours (Terradellas et al., 2016).

Ensemble multi-model products are generated daily by the NAMEE regional centre after bilinearly interpolating all forecasts to a common grid mesh of 0.5º x 0.5º. Multi-model forecasting intends to alleviate the shortcomings of individual models while offering an insight into the uncertainties associated with a single-model forecast. Centrality products (median and mean) aim to improve the accuracy of the single-model approach to forecasting.

Spread products (standard deviation and range of variation) indicate whether forecast fields are consistent within multiple models, in which case there is greater confidence in the forecast. Graphic examples of forecast outputs are presented in **Figures 33** and **34**.

5 See https://sds-was.aemet.es/

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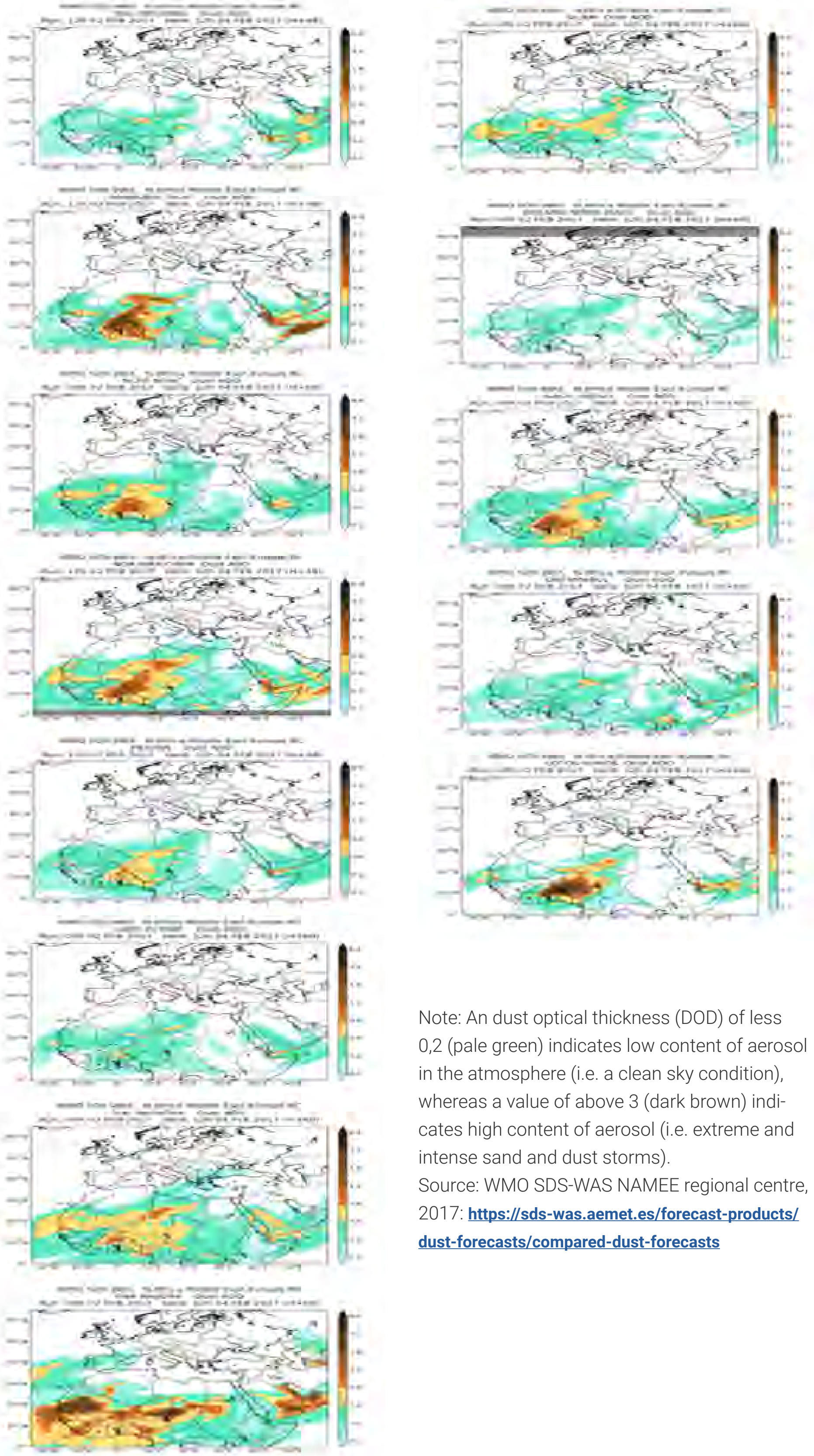
Figure 33. SDS-WAS forecast comparison of dust optical depth at 550 nm for 4 February 2017 at 12 UTC



Note: An dust optical thickness (DOD) of less 0,2 (pale green) indicates low content of aerosol in the atmosphere (i.e. a clean sky condition), whereas a value of above 3 (dark brown) indicates high content of aerosol (i.e. extreme and intense sand and dust storms).
Source: WMO SDS-WAS NAMEE regional centre, 2017: **https://sds-was.aemet.es/forecast-products/dust-forecasts/compared-dust-forecasts**

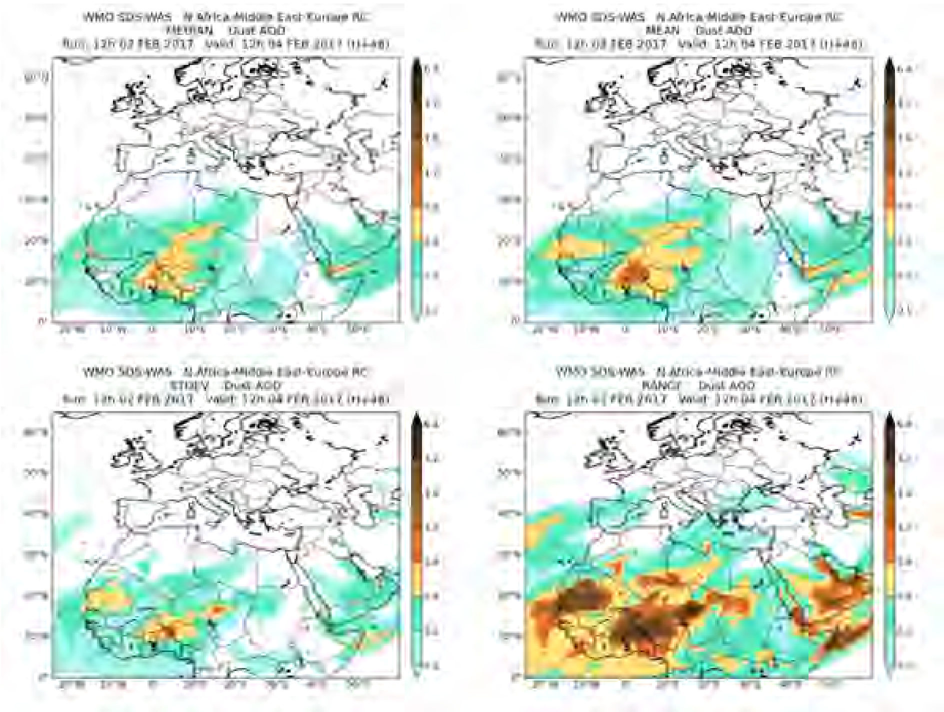


Figure 34. SDS-WAS multi-model ensemble products for 4 Feb 2017 at 12 UTC: median and mean (top), standard deviation and range of variation (bottom)

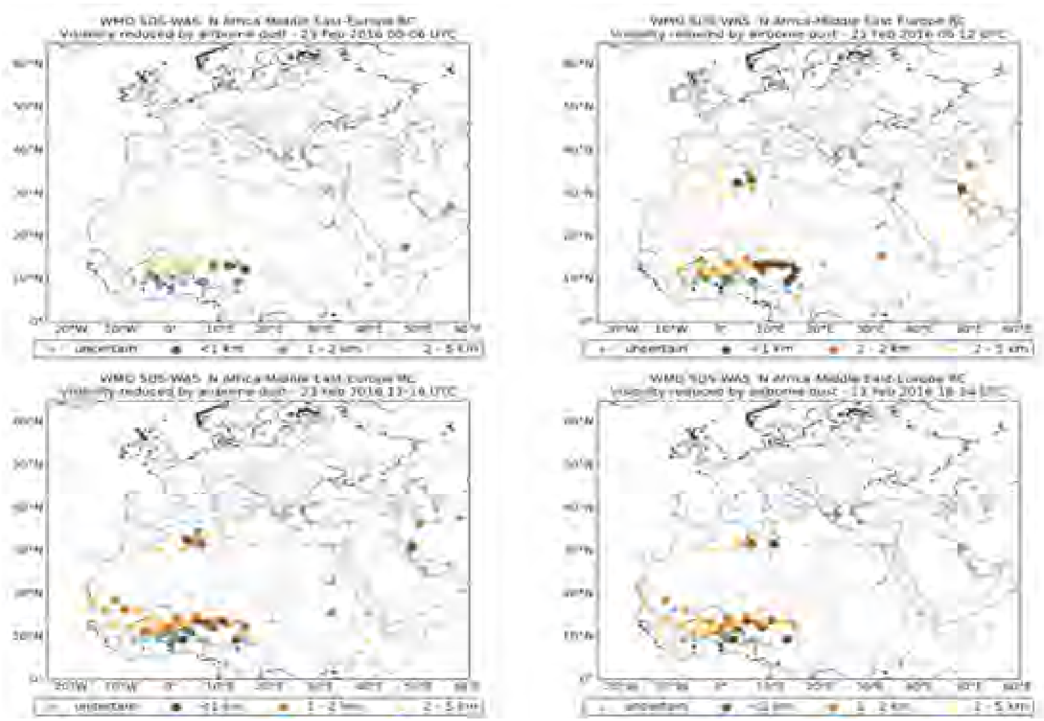
Source: SDS-WAS NAMEE regional centre, 2017: **https://sds-was.aemet.es/forecast-products/dust-forecasts/multimodel-products**

An important step in forecasting is evaluating the results that have been generated. The dust optical depth (DOD) forecasts are first compared with the aerosol optical depth (AOD) provided by the Aerosol Robotic Network (AERONET) (Holben et al., 1998; Dubovik and King, 2000) for a set of selected dust-prone stations located in Northern Africa, the Middle East and Southern Europe (Terradellas et al., 2016; Basart et al., 2017).

A system to evaluate the performance of the different models has been implemented. Different evaluation scores are computed in order to quantify the agreement between predictions and observations for individual stations, for three regions (Sahara-Sahel, West Asia and the Mediterranean) and for the whole reference area, as well as for different timescales (monthly, seasonal and annual). An evaluation system based on satellite products has also been implemented. Specifically, it uses two different aerosol retrievals based on the MODIS spectrometer travelling on board the Terra and Aqua satellites operated by the National Aeronautics and Space Administration (NASA).

Since October 2015, the WMO SDS-WAS NAMEE regional centre has released maps covering a six-hour period that indicate the weather stations in its geographical domain that report visibility reduced to less than 5 km associated with the presence of airborne sand and dust. **Figure 35** shows the maps of 23 February 2016, where dust activity is evident in the Sahel, the Maghreb and West Asia.

Figure 35. Six-hourly maps of visibility reduced to less than 5 km associated with airborne sand and dust for 23 February 2016



Source: SDS-WAS NAMEE regional centre, 2016: https://sds-was.aemet.es/forecast-products/dust-observations/visibility

Since October 2018, a warning advisory system for airborne dust has been available in Burkina Faso. Every day, two colour-coded maps with the warning levels for the next two days (D+1 and D+2) are produced. This clear, concise information helps with planning any activities vulnerable to airborne dust and can activate services and procedures aimed at mitigating damages caused to agriculture, public health or any other vulnerable sector. The warning advisory levels are based on the multi-model median forecast and are set according to the highest concentration value expected for the day. The warning advisory thresholds have been calculated based on a percentile-based approach calculated from the time series of the multi-model median between 2013 and 2017 (Terradellas et al., 2018).

Each of Burkina Faso's 13 administrative regions is colour-coded on the map (see **Figure 36**) to represent one of four levels of warning advisory:

- red to indicate extremely high concentrations of airborne dust (corresponding to values above the 97.5th percentile)
- orange to indicate very high concentrations (corresponding to values above the 90th percentile)
- yellow to indicate high concentrations (corresponding to values above the 80th percentile)
- green to indicate normal dust concentration

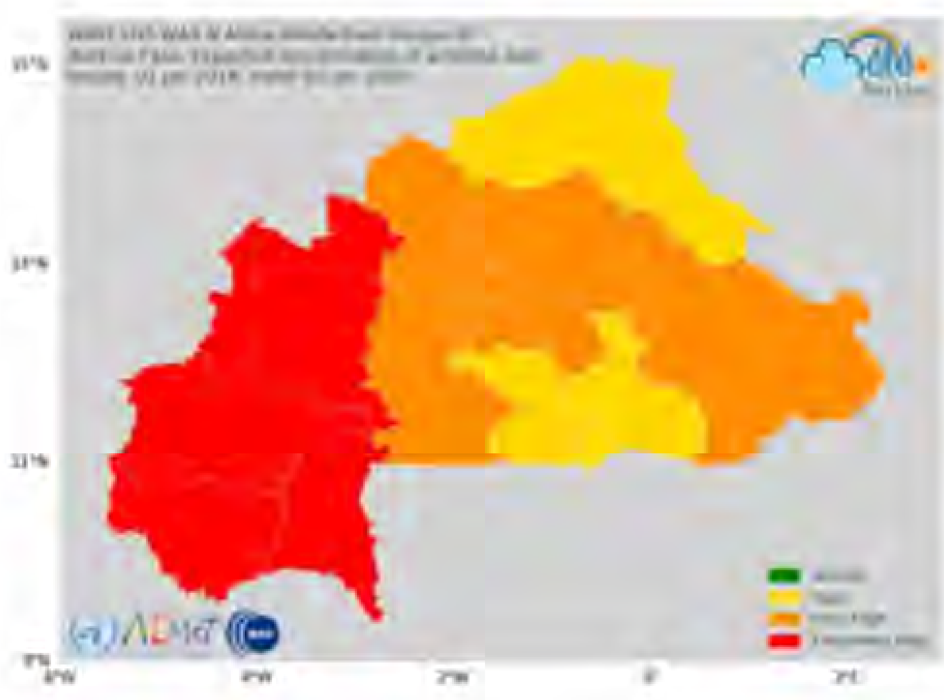


Figure 36. Burkina Faso dust forecast for 3rd January 2018

Source: SDS-WAS NAMEE regional centre, 2018: https://sds-was.aemet.es/forecast-products/burkina-faso-warning-advisory-system?date=

9.4.3. WMO SDS-WAS regional centre for Asia

The WMO SDS-WAS regional centre for Asia was launched in 2008, hosted by the China Meteorological Administration in Beijing.[6] The Asia SDS-WAS node's regional steering group includes representatives of China, Japan, the Republic of Korea, India, Mongolia and Kazakhstan.[7] In 2017, the WMO Executive Council also approved the operational status of the Beijing SDS-WAS regional centre for Asia as the WMO Regional Specialized Meteorological Centre with activity specialization on Atmospheric Sand and Dust Forecast (RSMC-ASDF Beijing), which is hosted by China. It has Central and Eastern Asia and some parts of Western Asia as its geographic domain.

Two regional models and four global models provide forecasts every three hours of DSC and DOD at 550 nm, operationally, at the RSMC-ASDF Beijing. Information on sand and dust is collected daily and used in six numerical models to produce regular reports.

The RSMC-ASDF Beijing covers the primary dust sources in the Asian region, and transport routes and deposition zones up to the Central Pacific. It covers DSC and DOD with a three-hour frequency and a lead time of up to 72 hours. The initiative is aimed at facilitating the development of the forecasting techniques and improving the forecast accuracy within the SDS-WAS regional node for Asia.

6 See http://eng.nmc.cn/sds_was.asian_rc/

7 See http://www.wmo.int/pages/prog/arep/wwrp/new/documents/Asian_Node_RSG_member_updated_Sept_2016.pdf

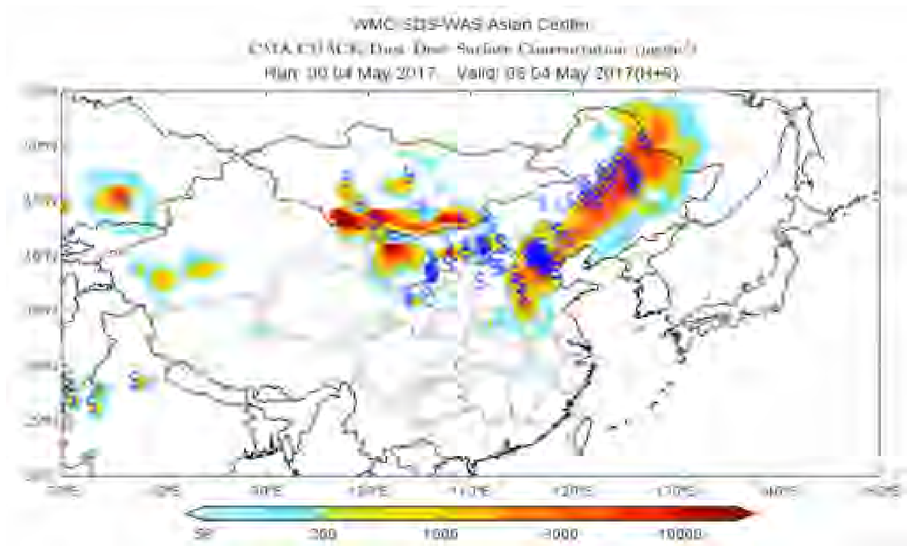
Dust forecasts are evaluated using an approach that differs from that used by the NAMEE regional centre, mainly because Asian dust is affected by relatively more substantial anthropogenic activities, even in the source area, while the AOD used in the NAMEE regional centre does not entirely represent the dust aerosol in Asia. A thread scoring system based on different observational sources has been integrated into a geographical information system. The observational data set consists of regular surface weather reports, PM mass concentration data, AOD retrievals from the China Aerosol Remote Sensing Network (CARSNET), retrievals from the Fēngyún (FY) satellites and lidar data.

Four categories of dust event have been defined:

1. Suspended dust: horizontal visibility less than 10 km and very low wind speed
2. Blowing dust: visibility between 1 and 10 km
3. Sand and dust storm: visibility less than 1 km and
4. Severe sand and dust storm: visibility less than 500 m (Wang et al., 2008).

Figure 37 shows an SDS verification system that was developed based on ground-based SDS observational data and supplemented with SDS data retrieval from the FY-2C satellite (Wang et al., 2008).

Figure 37. Verification of a dust forecast released by the CUACE[34]/dust model with surface SDS observational data from meteorological stations



Dust concentration – microgram per cubic meter

Notes: The S-like symbol denotes the routine observed SDS event by surface meteorological stations.
Source: SDS-WAS regional centre for Asia, 2017: **http://eng.nmc.cn/sds_was.asian_rc/**

9.4.4. SDS-WAS Pan-American regional centre[8]

The SDS-WAS Pan-American regional centre,[9] based at the Caribbean Institute for Meteorology and Hydrology in Barbados, conducts an exercise that is similar to the other two regional centres. This institute provides seven-day regional forecasts of

surface dust, $PM_{2.5}$, PM_{10} and ozone (O_3) concentration for the Caribbean using the advanced Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) (**Figure 38**).

8 Chinese Unified Atmospheric Chemistry Environment for Dust

9 See http://sds-was.cimh.edu.bb/

However, in addition to the regional focus, the Barbados centre will provide information for, and links to, global SDS-WAS forecasts based on three US global

models run by NOAA, NASA and the US Navy, as well as the ensemble of global research
models of the International Cooperative for Aerosol Prediction (ICAP).

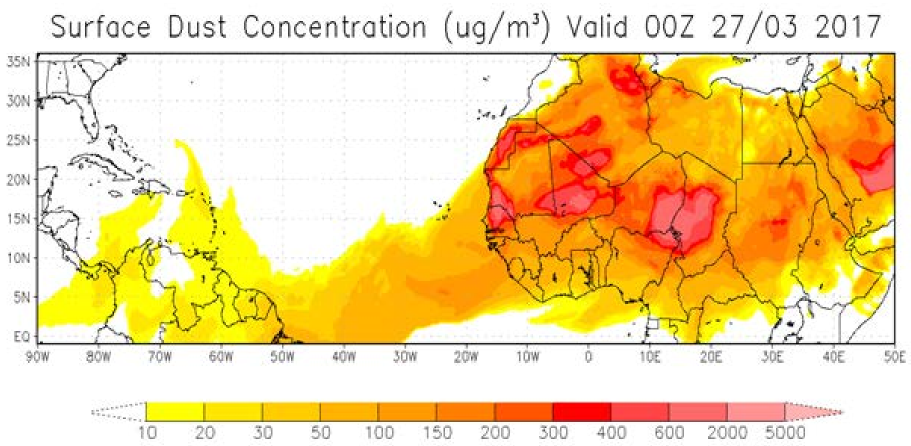
In accordance with the aims of the SDS-WAS, the Barbados centre is a node for collaboration across the Americas, working with other SDS-WAS centres to:

- develop, refine and distribute to the global community products that are useful in reducing the adverse impacts of SDS, and
- assess the impacts of SDS on society and nature

The centre's highest priority is addressing the adverse health implications of airborne dust in the region, which experiences both local-source dusts, such as from the Mojave, Sonoran and Atacama deserts, and imported dusts from arid lands of other continents, such as from the deserts of Asia and Africa (**Figures 38** and **39**).

Every year, storms in Africa transport 40 million tons of dust from the Sahara Desert to the Amazon Basin over 8,000 km away. Dust is carried to the Caribbean in spring/summer and to the south-eastern United States of America in summer.

High-latitude dust in places such as Greenland is also a concern for this region, but is an aspect of SDS that is sometimes overlooked.

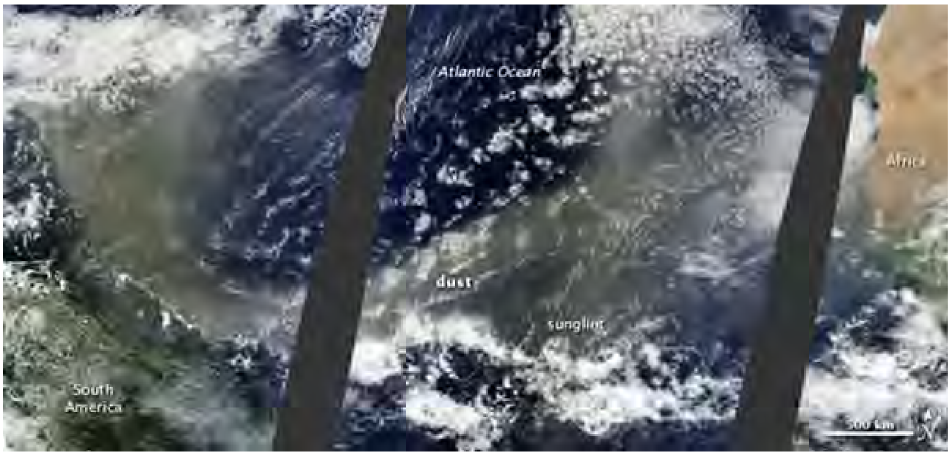


Dust concentration – microgram per cubic meter

Figure 38. Seven-day surface dust concentration forecast from the Caribbean Institute for Meteorology and Hydrology WRF-Chem model

Source: http://sds-was.cimh.edu.bb/

Figure 39. Movement of dust from the Sahara Desert (right) to the Amazon Basin (left)



Source: J. Schmaltz and R. Lindsey, MODIS Rapid Response Team, NASA (2017).

9.4.5. Regional Specialized Meteorological Centres with activity specialization on Atmospheric Sand and Dust Forecast

In 2013, the positive results obtained by the WMO SDS-WAS demonstrated the feasibility of the SDS forecast approach and identified the need to start developing operational services beyond the scope of research and development (Terradellas et al., 2016). This resulted in WMO establishing the designation process and the mandatory functions of Regional Specialized Meteorological Centres with activity specialization on Atmospheric Sand and Dust Forecast, otherwise known as RSMC-ASDF (WMO, 2015).

The basic mandatory functions of RSMC-ASDF are to:

- Prepare regional forecast fields using a dust forecast model continuously throughout the year, on a daily basis. The model shall consist of a numerical weather prediction (NWP) model incorporating online parametrizations of all the major phases of the atmospheric dust cycle.
- Generate forecasts, with an appropriate uncertainty information statement, of the following minimum set of variables: dust load (kgm^{-2}), dust concentration at the surface (µgm$-^{3}$), DOD at 550 nm, and three-hour accumulated dry and wet deposition (kgm$-^{2}$). Forecasts shall cover the period from the forecast starting time (00 and/or 12 UTC) up to a forecast time of at least 72 hours, with an output frequency of at least three hours. They shall cover the whole designated area. The horizontal resolution shall be finer than about 0.5x0.5°°.
- Disseminate through the Global Telecommunication System – WMO Information System (GTS-WIS) and provide on its web portal the forecast products in pictorial form not later than 12 hours after the forecast starting time.
- Issue an explanatory note on the web portal when operations are stopped due to technical problems.

There are currently two RSMC-ASDF:

- RSMC-ASDF Barcelona (Barcelona Dust Forecast Centre, https://dust.aemet.es), which started operations in 2014. The Barcelona Dust Forecast Centre is a joint initiative of the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Center (BSC). It provides daily dust forecasts for Northern Africa (north of the equator), the Middle East and Europe, based on the in-house BSC Multiscale Nonhydrostatic AtmospheRe CHemistry model (NMMB-MONARCH).

- RSMC-ASDF Beijing (Beijing Dust Forecast Centre, http://eng.nmc.cn/sds_was.asian_rc/) started operations in 2016. It is managed by the China Meteorological Administration and provides dust forecasts for Asia using six numerical models.

Additional details on the operations of the two RSMC-ASDF can be found by clicking on the web links in the descriptions above.

Figure 40 identifies the location of regional WMO SDS-WAS nodes in Barcelona, Beijing and Bridgetown as well as several key forecasting centres that contribute to global and regional SDS-WAS forecasting, information and guidance. The regional nodes are denoted by red boxes.

In addition to national centres, research groups and the SDS-WAS centre, the European Centre for Medium-Range Weather Forecasts (ECMWF) provides global daily aerosol forecasts including dust forecasts. See **Box 14** for more details.

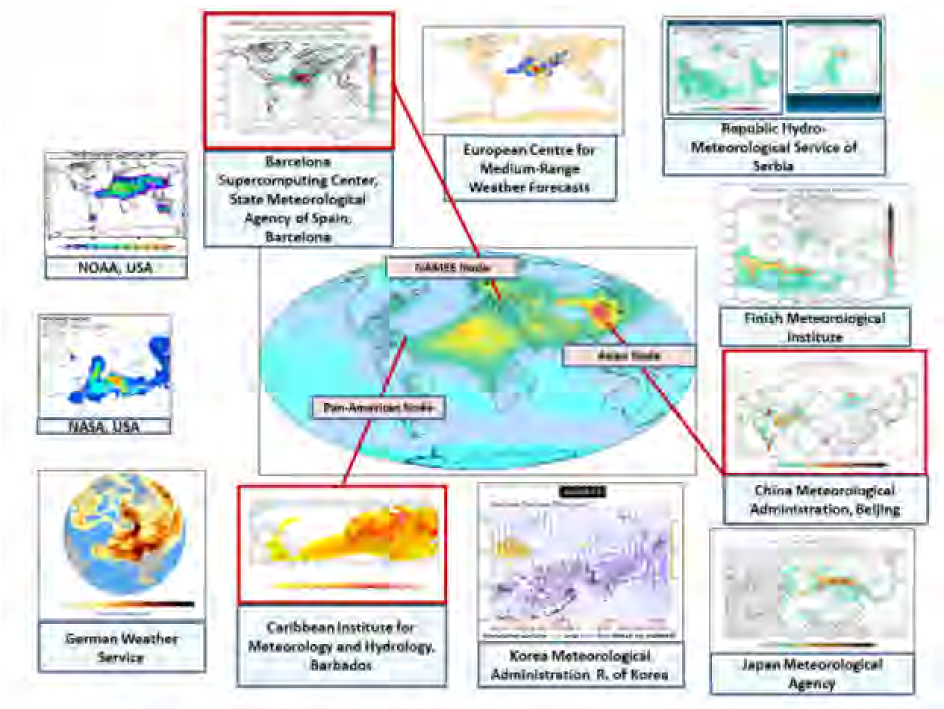


Figure 40. Regional WMO SDS-WAS nodes in Barcelona, Beijing and Bridgetown several key forecasting centres that contribute to global and regional SDS forecasting, information and guidance

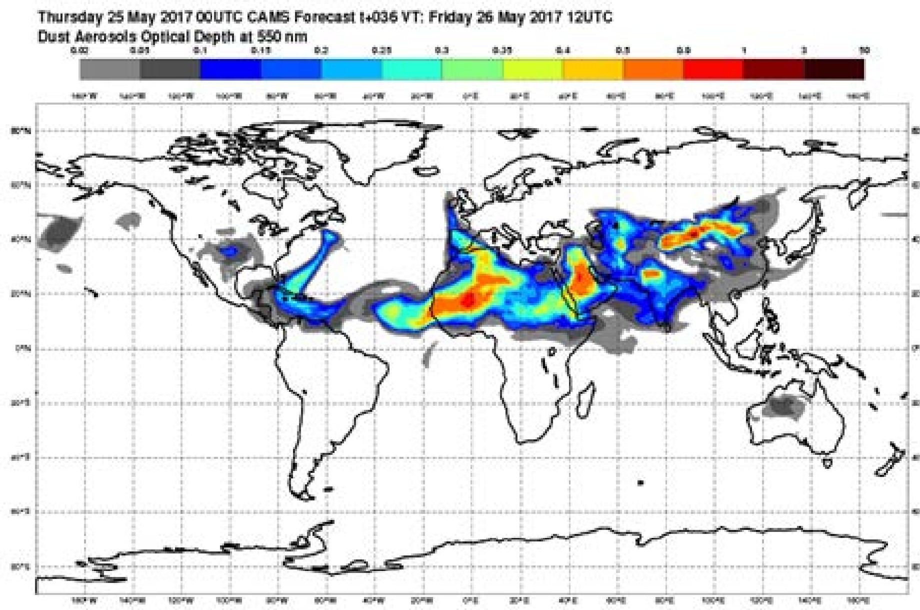
Source: WMO SDS-WAS: **www.wmo.int/sdswas**

Box 14. Copernicus Atmosphere Monitoring Service: a European initiative

Since 2008, the ECMWF has been providing daily aerosol forecasts (including dust forecasts) as part of successive European Union-funded projects. A detailed description of the forecast and analysis model, including aerosol processes, is provided in Morcrette et al. (2009) and Benedetti et al. (2009).

These efforts have made it possible to incorporate dust forecasts into the operational Copernicus Atmosphere Monitoring Service (CAMS), which provides daily global dust forecasts up to five days in advance and contributes to the WMO SDS-WAS. All data are publicly available online at https://atmosphere.copernicus.eu/ and on the SDS-WAS centres' websites. An example is shown below.

Figure 41. Dust aerosol optical depth 36-hour forecast for 26 May 2017 at 12 UTC provided by CAMS



Source: CAMS, 2017: **https://atmosphere.copernicus.eu/**

9.5 National meteorological and hydrometeorological services

9.5.1. Government weather services

National meteorological and hydrometeorological services (NMHS) are responsible for formulating SDS forecasts and issuing warnings at the national level. For more on SDS early warning, see **chapter 10.**

NMHS can access guidance on SDS-WAS forecasting from the SDS-WAS centres and via the WMO website (https://www.wmo.int/pages/prog/arep/sdswas/). These outputs, together with any modelling done by NMHS, can be used in daily and near-term (up to three days) forecasting for SDS.

The capacity of NMHS to manage the SDS data analysis and forecasting process can vary considerably. **Box 15** summarizes how the Korea Meteorological Administration manages this process.

Depending on the size of a country and its NMHS capacities, forecasts and warnings may be developed at the subnational (provincial or state) level.

Box 15. Dust monitoring and forecasting system of the Korea Meteorological Administration

The Republic of Korea Meteorological Administration (KMA) monitors and forecasts Asian dust in four stages:

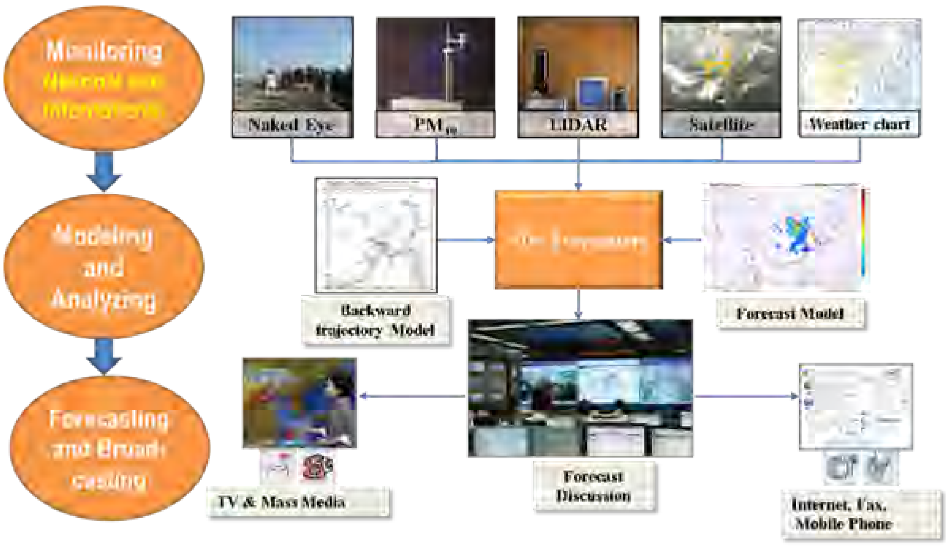
First, the KMA uses Asian dust observations made by the naked eye as well as PM_{10} concentrations from the China-KMA Joint SDS Monitoring Network located in the SDS source regions and along the pathways to Korea.

Second, the KMA also uses international meteorological information from the Global Telecommunication System (GTS) at three-hour intervals and satellite images from the Communication, Ocean and Meteorological Satellite (COMS), NOAA, Himawari-8 and Aqua & Terra/MODIS to identify the location and intensity of Asian dust.

Third, the supercomputer-simulated Asian Dust Aerosol Model (ADAM) results are fed to the KMA intranet to be utilized for Asian dust forecasting and to the WMO SDS-WAS Asian centre to be included in its regional ensemble.

Finally, PM_{10} concentrations from 29 sites and particle counter data from seven sites are utilized to identify the path and intensity of Asian dust.

The KMA's Asian Dust Warning System uses the results of the monitoring and forecasting system to issue warnings when the hourly average dust (PM_{10}) concentration is expected to exceed 800 µg/m^3 for over two hours. When the KMA issues a warning, the information is shared with the public and broadcasting companies online, including through social networking services.



These forecasts and the associated warning information need to be linked to subnational (provincial, state) disaster management authorities, as well as other organizations and actors involved in dealing with SDS.

The issuance of impact-based SDS forecasts and warnings at the national and subnational levels requires strong collaboration among the NMHS, national disaster management authorities and other national stakeholder organizations that hold data on SDS vulnerability and exposure, which may be necessary in order to assess the impact of SDS. Where NMHS modelling and forecasting capacities may be limited, SDS-WAS products can be used to directly support NMHS with local forecasting.

For example, the WMO SDS-WAS NAMEE regional centre supports the Burkina Faso National Meteorological Agency regarding the aforementioned warning advisory system for airborne dust in the country.

9.5.2. Commercial weather services

Commercial weather services can also provide SDS warnings to the general public. For instance, the Weatherzone® website provided forecasts and information on a dust storm affecting Sydney in November 2018.[10] These services can also inform the public about SDS more generally, for example the AccuWeather® website explains Saharan dust.[11] Significantly, non-NMHS sources may disagree with official sources on SDS forecasts: although many commercial weather reports are derived from official NMHS reports or information, they can also be developed from modelling and information systems that operate in parallel to government or WMO systems.

Commercial forecasts are significant for the SDS warning process insofar as, in some cases, SDS information may be made quickly and widely available to the general population through commercial forecasts on public media such as commercial radio, TV or mobile phones (where people may be able to purchase a service providing weather forecasts). This requires that NMHS and commercial forecasters collaborate to ensure warning messages are accurate, recognizing that more accurate information, disseminated through more channels, is generally preferable to the opposite.

To ensure that SDS forecasts are consistent and SDS warnings are timely, accurate and coordinated, NMHS and commercial forecasters working in a country should develop a coordinated forecast and warning dissemination plan (see **chapter 10**). This plan may also need to include forecasting coming from outside a country when warnings are commonly provided from these sources, for example through global media.

9.5.3. Voluntary observations

Voluntary observations are used to develop both NMHS and commercial weather services' forecast and warnings products. One example of a voluntary SDS observation system is the Community DustWatch network in Australia, which uses a citizen science approach, involving the use of trained volunteers to collect scientific data. This provides a cost-effective method to address gaps in data collection and reporting on SDS.

The Community DustWatch network provides instruments and observer reports on SDS which complement information collected through the Australian Bureau of Meteorology's system. Observer reports can be provided in near real-time or as after-the-fact reports. The former can be used for SDS forecasting and warning, while the latter can be used to support research into SDS.

10 http://www.weatherzone.com.au/news/dust-storm-begins-to-impact-sydney-as-nsw-government-issues-air-quality-warning/528801

11 https://www.accuweather.com/en/health-wellness/everything-you-need-to-know-about-saharan-dust/764481

Additional details are available from the Community DustWatch website.

9.6 SDS modelling

9.6.1. Introduction

The sections below provide an overview of the use of models for SDS forecasting. Regional SDS forecast centres (for example, Barcelona and Beijing) use models to develop their forecasts of SDS activity. Models considering global climate conditions also need to incorporate sand and dust to understand how SDS can affect climate, and how the climate is changing.

As discussed in Benedetti et al. (2014), several reasons have motivated the development of dust modelling/forecasting capabilities for short-term forecasts and for long-term impact assessments:

- Decision makers have long desired the ability to forecast severe dust events in order to issue early warnings and mitigate their impacts.
- There is a pressing need to monitor the Earth's environment to better understand changes and adapt to them, especially in the context of climate.
- While the importance of dust–climate interactions has long been recognized (Intergovernmental Panel on Climate Change [IPCC], 2007; 2013), it is only more recently that the importance of feedback mechanisms between dust and atmosphere for weather forecasting has been highlighted (Pérez et al., 2006; Nickovic et al., 2016).

SDS observations have only a limited capacity to monitor SDS, as they help assess SDS evolution only several hours in advance using simplified spatial and temporal extrapolation of their features. The short nature of this approach is too limiting to provide complete and effective SDS warnings.

To extend the time validity of SDS early warnings to short-term (up to three days) and medium-term (up to 10 days in advance) periods, the natural response was to extend the capabilities of the NWP models so that they are able to predict concentrations of atmospheric constituents such as mineral dust.

9.6.2. Development of SDS modelling

Over the last decade, a dozen numerical modelling systems for sand and dust forecasting have been developed. Most models use atmospheric weather prediction models as an online driver. Dust particle distribution is introduced in the models as a common component. The dust mass conservation equation is embedded as one of the model governing equations (Nickovic et al., 2001; Tegen and Schulz, 2014). To simulate the SDS processes, advanced numerical parameterization methods are used.

Monitoring the process of SDS, obtaining the relevant parameters of its occurrence, development and change, providing the observational basis for describing the weather process of SDS, carrying out numerical dust forecasts and providing corresponding SDS early warnings are urgently required if we are to effectively mitigate the impact of SDS and prevent and reduce disasters. These activities are also of great significance to national decision-making on how the impact of SDS can be addressed.

The first dust forecasting systems with regional (Nickovic, 1996; Nickovic and Dobricic, 1996) and global (Westphal et al., 2009) model domains were introduced in the 1990s. Since then, numerical model-based dust forecasts have become available in many national meteorological services and research centres around the world (Benedetti et al., 2014).

Due to the progressive increase in available computing power, models are run every day with greater horizontal and vertical resolutions in order to better describe small-scale processes, such as the effect of cold outflows from thunderstorms on dust emission. Some forecasting systems also assimilate satellite and ground-based observations so that they have a much better description of the dust content in the initial state and can therefore predict its evolution more accurately.

Despite extensive efforts in recent years, dust predictions still lack the accuracy of ordinary weather forecasts. Besides, the prediction of surface concentration – which is the key parameter for most applications – is much less accurate than that of columnar parameters, such as dust load or optical thickness.

One of the methods being worked on to improve forecast skills is ensemble prediction, which aims to describe the future state of the atmosphere from a probabilistic point of view. Multiple simulations are run to account for the uncertainty of the initial state and/or for the inaccuracy of the model and the mathematical methods used to solve its equations (Palmer et al., 1993).

Two dust multi-model ensemble systems are currently in operation:

1. The WMO SDS-WAS multi-model ensemble, operated by the SDS-WAS NAMEE regional centre, based on 12 regional and global models (Terradellas et al., 2016; Basart et al., 2019).
2. The International Cooperative for Aerosol Prediction's multi-model ensemble (ICAP MME). This is a consensus-style forecast generated from eight global NWP models that include mineral dust as well as other aerosol species (Sessions et al., 2014).

9.6.3. Overview of numerical dust models

The impacts of dust on the Earth's radiation balance, atmospheric dynamics, biogeochemical processes and atmospheric chemistry are only partly understood and remain largely unquantified. An assessment of the various effects and interactions of dust and climate requires quantification of global atmospheric dust loads and their optical and microphysical properties.

Dust distributions that are used in assessments of dust effects on climate usually rely on results from large-scale numerical models that include dust as a tracer. Over the last few years, numerical prediction of dust concentration has become prominent at several research and operational weather centres due to growing interest from diverse stakeholders, such as solar energy plant managers, health professionals, aviation and military authorities, and policymakers. Including dust transport interaction with the atmosphere in numerical models can improve the accuracy of weather forecasts and climate simulations and help improve understanding of the environmental processes caused by mineral dust (Knippertz and Stuut, 2014).

To estimate the impact of dust on the Earth system, knowledge of atmospheric dust's life cycle (including dust source activation and subsequent dust emission, dust transport routes, and dust deposition) is crucial. In order to correctly describe and quantify the dust cycle, one needs to understand equally well local-scale processes such as saltation and entrainment of individual dust particles, as well as large-scale phenomena such as mid- and long-range transport.

NWP and research on atmospheric dynamics models with an embedded dust component can be used to:

- study and predict processes that influence dust distribution (for example, haboobs) and
- assess the dust global budget, including the contribution of the different dust storms

Typically, dust mass concentration is added as a prognostic parameter and equations mathematically describe the most significant processes over time, such as dust emission, vertical turbulent mixing, long-range transport of dust in the free atmosphere, and wet and dry deposition to the Earth surface.

These complex mathematical models can predict the SDS process with reasonable accuracy and thus help to reduce hazardous impacts of SDS. The same kind of dust models are also used for climatic-scale projections and assessment and to investigate dust at large scale and for long-term changes (such as desertification).

9.6.4. Challenges facing SDS models

Dust models face a number of challenges owing to the complexity of the system, including:

- The physical processes involved in the dust cycle, particularly for dust emission, are not yet fully understood (also see **chapter 2**).
- The need for accurate, frequent and detailed weather forecasts.
- The vast range of scales required to fully account for all of the physical processes related to dust emission, transport and deposition (i.e. timescales ranging from seconds to weeks).
- The paucity of suitable dust observations available for model development, evaluation and assimilation, particularly for desert dust sources.
- The wide range of scales required to fully account for all processes related to SDS development. Dust production is a function of surface wind stress and soil conditions, but the wind is an extremely variable parameter in both space and time and soil properties are highly heterogeneous and not always well characterized.
- Soil conditions, which heavily impact dust emission, are not always well known in potential source areas (see **chapter 8**).

9.6.5. SDS models currently in use

There has been a considerable increase in the number and complexity of dust atmospheric models used for research and operational purposes (Nickovic at al., 2015). **Table 21** sets out the main global and regional SDS models used by different meteorological or research centres. Outputs from these models provide inputs for the WMO SDS-WAS system and its regional centres, as described elsewhere in this chapter.

©White Sands National Park, November 5th, 2016

Table 21. SDS atmospheric models contributing to the WMO SDS-WAS system and regional centres

Model	Institution	Domain	Data assimilation
BSC-DREAM8b_c2	Barcelona Supercomputing Center	Regional	NO
CAMS-ECMWF	ECMWF	Global	MODIS-AOD
DREAM8-NMME-CAMS	South East European Virtual Climate Change Center (SEEVCCC)	Regional	YES (ECMWF dust-analysis)
NMMB/MONARCH	Barcelona Supercomputing Center	Regional	NO
MetUM	Met Office	Global	MODIS/Aqua
GEOS-5	NASA	Global	MODIS
NGAC	NOAA National Centers for Environmental Prediction (NCEP)	Global	NO
EMA REG CM4	Egyptian Meteorological Authority (EMA)	Regional	NO
WRF-Chem	National Observatory of Athens (NOA)	Regional	NO
SILAM	Finnish Meteorological Institute (FMI)	Global	NO
LOTOS-EUROS	TNO	Regional	NO
ICON-ART	Deutscher Wetterdienst (DWD)	Regional	YES (data assimilation cycle for dust, currently no AOD/dust obs. used)
CUACE	China Meteorological Administration (CMA)	Regional	three-dimensional variational (3D-VAR)
ADAM3	National Institute of Meteorological Sciences of the Korea Meteorological Administration (NIMS/KMA)	Regional	Optimal interpolation (OI)
MASINGAR	Meteorological Research Institute of the Japan Meteorological Agency (MRI/JMA)	Global	two-dimensional variational (2D-VAR)
NAAPS and ICAP ensemble	U.S. Naval Research Laboratory (NRL)	Global	YES
WRF-Chem	Caribbean Institute for Meteorology and Hydrology (CIMH)	Regional	NO

Source: Adapted from the WMO SDS-WAS website: www.wmo.int/sdswas

9.6.6. Scale of model results

Due to increased computing power, these models can be run at greater spatial resolutions to allow for more detailed investigations of smaller area processes, such as the effects of cold outflows from thunderstorms on dust emission (Heinold et al., 2013; Vukovic et al., 2014; Solomos et al., 2017). At the same time, there have been some new approaches to treating emission processes in the models at high resolution (Kok, 2011; Klose and Shao, 2016).

At global scales, models can reproduce the main dust transport pathways driven by large-scale flows (mainly associated with monsoon winds and frontal passages), showing that these storms are the main contributor to the dust global budget (Cakmur et al., 2006; Huneeus et al., 2011). However, the contribution of smaller-scale dust storms (such as those associated with convection in haboobs or dust whirlwinds) to overall dust flows is still uncertain (Knippertz and Todd, 2012).

In West Africa, both haboobs and the breakdown of nocturnal low-level jets (NLLJs) appear to account for 30 to 50 per cent of dust emissions in summer (Allen et al., 2013; Fiedler et al., 2013; Heinold et al., 2013; Marsham et al., 2013; Pope et al., 2016 Miller et al. (2008) estimated that the haboob activity in the Middle East in summertime could be responsible for 30 per cent of its dust emissions.

Dust whirlwinds (see **chapter 2**) are not easily identified in operational dust models and are still linked to large uncertainty in the modelling process (Knippertz and Todd, 2012; Jemmett-Smith et al., 2015; Klose and Shao, 2016). According to global estimates, microscale dust whirlwinds could contribute by ~26 per cent ± 18 per cent to total dust emissions (Koch and Renno, 2005). Recent studies (including Jemmett-Smith et al., 2015) estimate their global contribution at ~3.4 per cent (uncertainty range 0.9–31 per cent). Technogenic smaller-scale dust storms (< 1 km) are usually local-scale phenomena and require high-resolution meso-scale computer fluid dynamics (CFD) type models for such SDS assessments (see, for example, Amosov et al., 2014).

9.6.7. Reanalysis products and SDS modelling

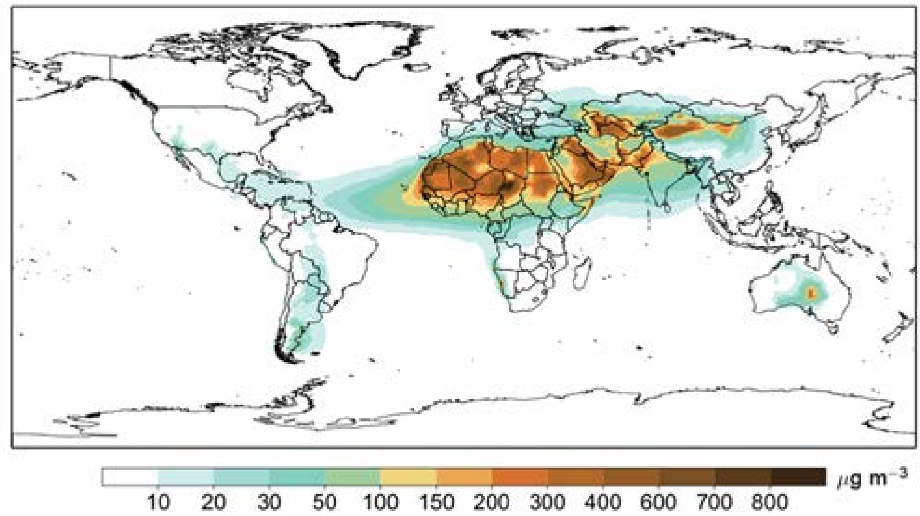
Reanalysis products are also used for long-term impact assessments of SDS and are increasingly being used for climate monitoring and assessment.

Reanalysis is the process whereby an unchanging data assimilation system is used to provide a consistent reprocessing of meteorological and atmospheric composition observations, typically spanning an extended segment of the historical data record.

The process relies on an underlying forecast model to combine disparate observations in a physically consistent manner, enabling the production of gridded data sets for a broad range of variables, including ones that are sparsely or not directly observed (Gelaro et al., 2017). Two global reanalyses that include dust content are:

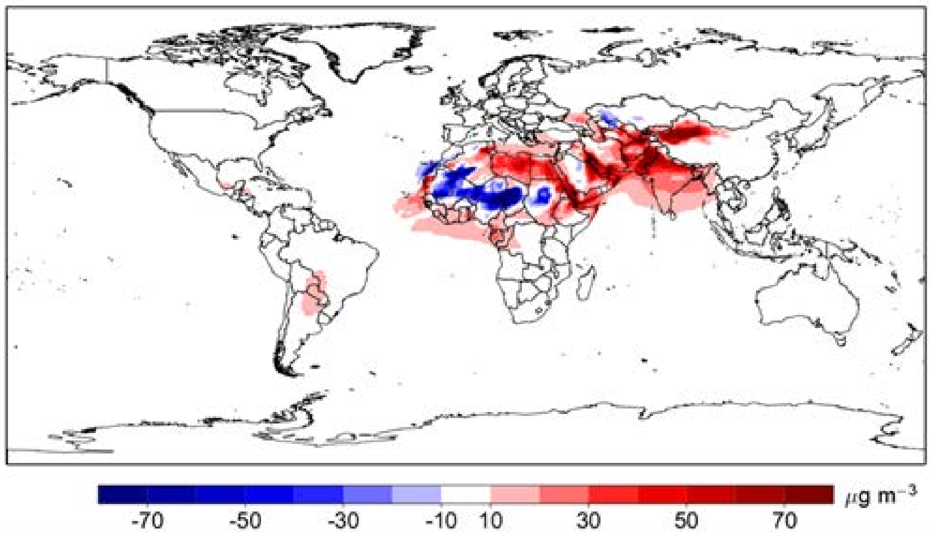
- NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), which provides data beginning in 1980, is the latest atmospheric reanalysis version for the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO) (Gelaro et al., 2017), (see **Figures 42** and **43**), and the
- Copernicus Atmosphere Monitoring Service (CAMS) reanalysis, which started in 2003.

Figure 42. Annual mean surface concentration of mineral dust in 2018 calculated by the SDS-WAS regional centre for Asia, based on NASA MERRA reanalysis



Source: WMO Airborne Dust Bulletin, 2019.

Figure 43. Anomaly of the annual mean surface concentration of dust in 2018 relative to mean of 1981–2010, calculated by the SDS-WAS regional centre for Asia, based on NASA MERRA reanalysis



Source: WMO Airborne Dust Bulletin, 2019.

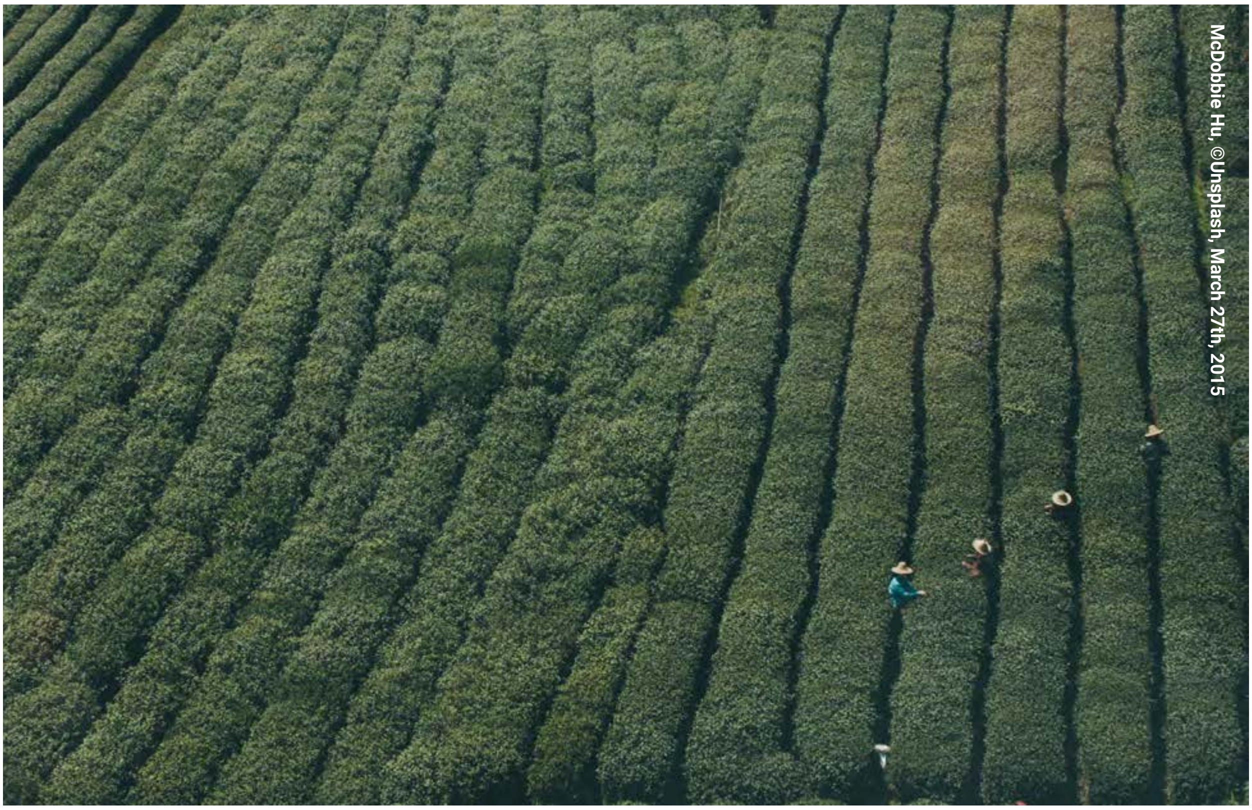
9.7 Conclusions

SDS forecasting focuses on the impacts of weather on people, framed as impact-based, human centred forecasting. This approach provides individuals at risk from SDS with information on emerging SDS as well as on actions that can be taken to address the expected impacts of SDS.

There is a range of in situ and remote options to collect data on SDS events, each with specific advantages. Three WMO SDS-WAS regional centres (in Barcelona, Beijing and Barbados) collect and process data from in situ and remotely sensed sources to develop products that support SDS forecasting at a regional level. They also support countries with national-level forecasting and issuing their own warnings.

While some countries are capable of developing their own forecasts, a majority use SDS-WAS products to improve impact-based, people-centred forecasting and reduce the impacts of SDS on lives and well-being.

SDS modelling has made rapid progress and involves a number of models and reanalysis as part of efforts to improve the understanding of SDS and provide useful forecasts which feed into effective warning results. A number of challenges with the modelling process remain, particularly linked to small SDS events (such as dust whirlwinds) and accounting for soil and local weather (particularly wind) conditions. However, current model outputs provide a significant contribution of SDS forecast and monitoring outputs through the WMO SDS-WAS system and for some NMHS.



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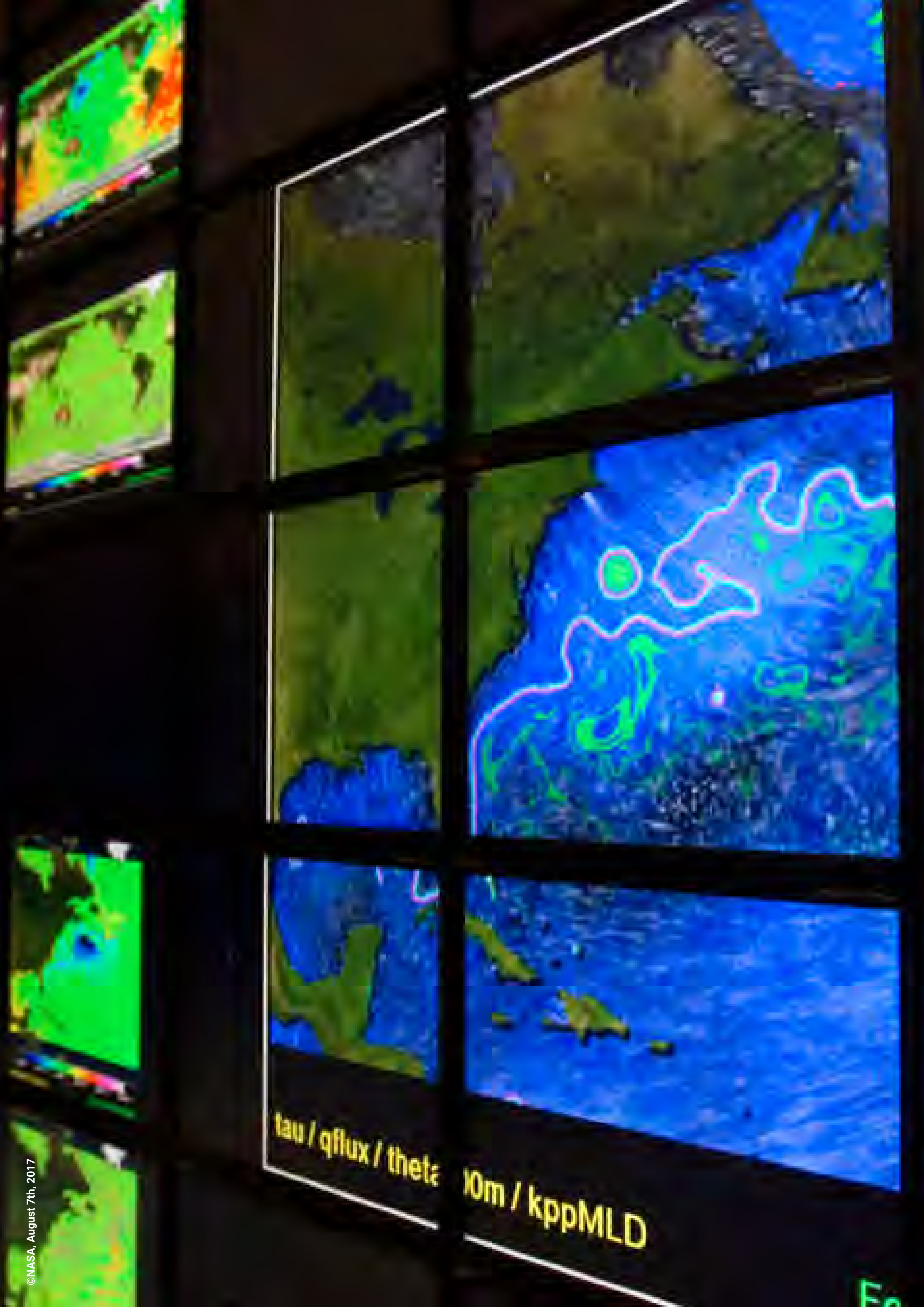
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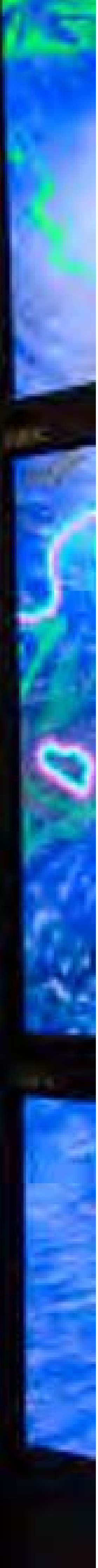

10. Sand and dust storms early warning

Chapter overview

The chapter provides a general overview of requirements for a sand and dust storms (SDS) warning system involving national meteorological and hydrological services (NMHS), national disaster management authorities (NDMAs) and a wide range of other stakeholders. The effectiveness of a warning system is demonstrated by how well individuals and other parties at risk take preventive actions to mitigate risks once a warning is received. The chapter discusses responsibilities for forecasts and warnings, warning dissemination, people-centred, impact-based warning, warning verification and the process by which individuals take action once a warning has been received. While the chapter content is general, it provides core guidance on developing SDS warning systems at the national or subnational levels.

10.1. Introduction

Warnings are a core part of disaster risk management processes, provided they are disseminated early enough to permit actions to reduce or avoid the impacts of hazards. This chapter provides an overview of early warning approaches to sand and dust storms (SDS) based on generally accepted practices.

SDS warning systems are complex and can operate in different ways and with different actors, depending on the country involved. As a result, individual users and countries are expected to adopt the overall early warning system concept described below to best meet their needs and capacities. This chapter should be read together with **chapters 3**, **9**, **12** and **13**, as well as World Meteorological Organization (WMO) (2018), WMO (2017) and WMO (2015a; 2015b), which provide additional details on developing a multi-hazard early warning system (MHEWS). Reference should also be made to the WMO Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS) and its operational centres within the WMO Global Data-processing and Forecasting System (GDPFS) (see **chapter 9**).

10.2. Conceptualizing early warning for SDS

The core concept applied in early warning is that the individual at risk is the starting point for the warning process. The timing, content, reception and understanding of warnings should enable individuals, communities, businesses and organizations at immediate risk to take actions to reduce or avoid impacts from the risks they face (see **Box 16**).

While it can be difficult to ensure good and timely dissemination of warnings, individuals with a good understanding of warning factors can often initiate actions on their own to reduce or avoid SDS impacts.

As a result, at-risk individuals, communities, businesses and organizations should be empowered to understand warning signals and to take action to avoid or mitigate the impact of SDS. Educating individuals about SDS risks and warning signs, as discussed in this chapter, is an essential part of an effective early warning system.

Box 16. What is an early warning system?

An early warning system is "an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events".

Source: United Nations Office for Disaster Risk Reduction (UNDRR), 2018.

Traditional knowledge can also play a significant role in triggering warnings and taking action. This knowledge should be part of any warning system and should be used to integrate the overall warning process into the culture of individuals and societies that are the targets of a warning process.

The content of a warning message is dependent on (1) the knowledge (data and analysis) about weather events available to a forecaster, (2) the time available to take action, and (3) the nature of the actions to be taken.

Warnings of near-term events (minutes to days in advance) provide immediate guidance to at-risk populations to take action to address the expected impact of SDS. Such short-term (up to several days) warnings can be based on operational forecasts of dust concentrations (WMO, 2015a, also see **chapter 9**).

SDS warnings can also be based on medium- to long-term situations (months or longer). For instance, if data indicate a wetter than normal monsoon with expected early seasonal storms, a warning could be issued anticipating the development of more or more powerful haboobs at the beginning of the monsoon.

Based on seasonal warnings, individuals and institutions may take appropriate action, such as replacing filters or resealing windows to limit from entering buildings (see **chapter 13** for more on SDS preparedness and impact mitigation). This seasonal forecast would be followed by warnings when forecasts indicated actual haboob development or arrival at a location is expected.

An effective warning process is people-centred and impact-focused (WMO, 2018). The people-centred aspect recognizes that it is at-risk individuals who turn warning into action and that it is therefore the people who need to be involved in the design and operation of early warning systems from the start, making the last mile the first mile. The impact aspect of the warning system identifies how SDS can affect individuals, communities or assets, and what actions can be taken to reduce their threat.

10.3. Key components of early warning systems

An effective people-centred and impact-based early warning system has four components (United Nations General Assembly, 2016):

- detection, monitoring, analysis and forecasting, as discussed in **chapters 2**, **3**, **8** and **9**
- disaster risk and hazard knowledge, as discussed in **chapters 3**, **4**, **5**, **7**, **12** and **13**
- preparedness and response capacities as discussed in **chapter 13**
- warning dissemination and communication, as discussed in this chapter.

Figure 44 provides a set of core questions for each component as presented in **Multi-hazard Early Warning Systems: A Checklist** (WMO, 2018). The document was developed by several international organizations with a key role in early warning under the International Network for Multi-Hazard Early Warning Systems (IN-MHEWS) as an update of **Developing Early Warning Systems: A Checklist** (United Nations International Strategy for Disaster Reduction [UNISDR], 2006). The key questions for warning dissemination and communication are summarized in the lower left box of the figure.

An MHEWS addresses several hazards and impacts of similar or different types in contexts where hazardous events may occur alone, simultaneously, cascadingly or cumulatively over time, and takes into account the potential interrelated effects. The ability of an MHEWS to warn of one or more hazards increases the efficiency and consistency of warnings through coordinated and compatible mechanisms and capacities, involving various disciplines to ensure updated and accurate hazards identification and monitoring for multiple hazards (United Nations General Assembly, 2016).

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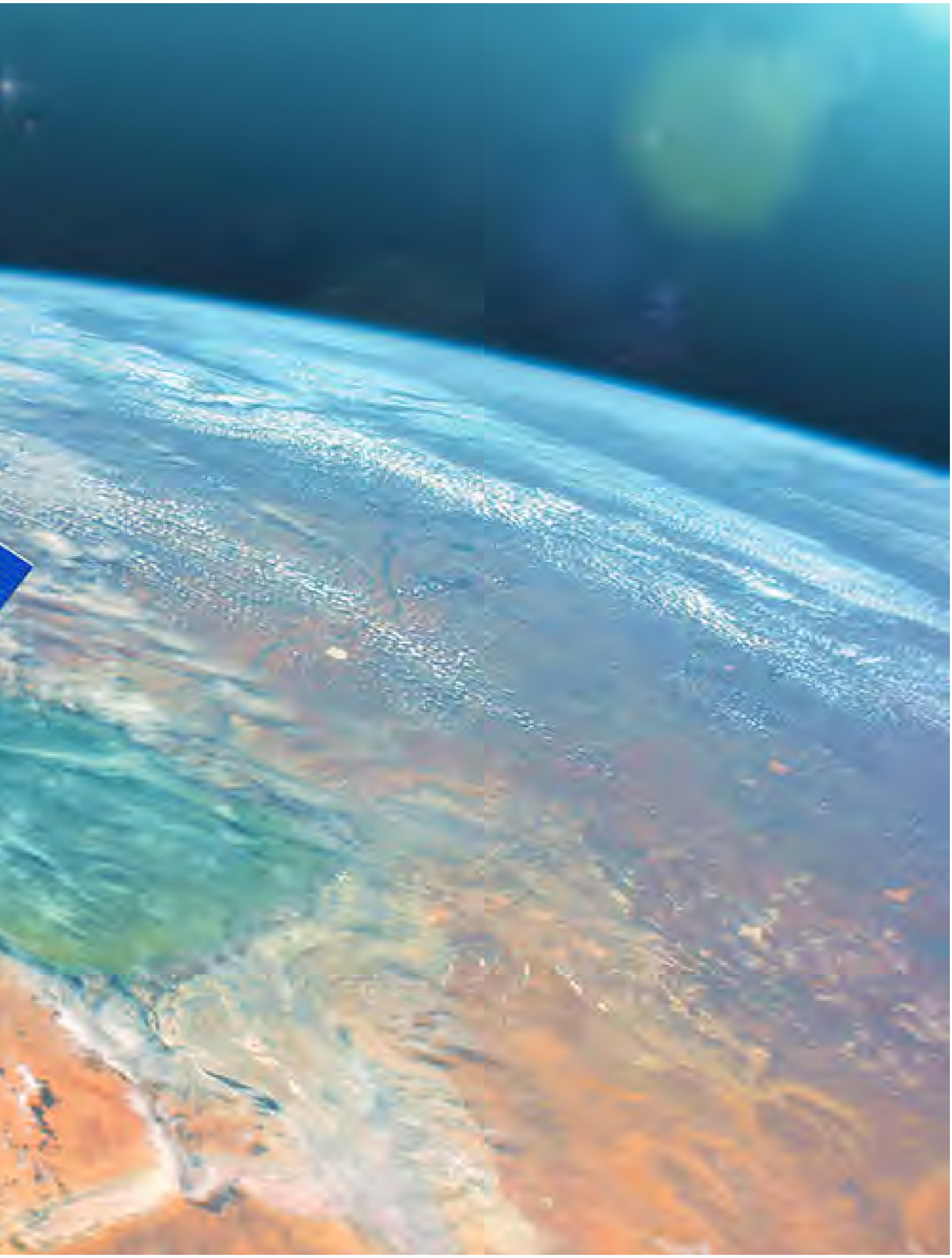


DISASTER RISK KNOWLEDGE

- Are key hazards and related threats identified?
- Are exposure, vulnerabilities, capacities and risks assessed?
- Are roles and responsibilities of stakeholders identified?
- Is risk information consolidated?

DETECTION, MONITORING, ANALYSIS AND FORECASTING OF THE HAZARDS AND POSSIBLE CONSEQUENCES

- Are there monitoring systems in place?
- Are there forecasting and warming systems in place?
- Are there institutional mechanisms in place?

WARNING DISSEMINATION AND COMMUNICATION

- Are organizational and decision-making processes in place and operational?
- Are communication systems and equiptment in place and operational?
- Are impact-based early warnings communicated effectively to promt action by target groups?

PREPAREDNESS AND RESPONSE CAPABILITIES

- Are disaster preparedness measures, including response plans, developed and operational?
- Are public awareness and education campaigns conducted?
- Are public awareness and response tested and evaluated?

Figure 44. Four elements of end-to-end, people-centred early warning systems

Source: United Nations International Strategy for Disaster Reduction (UNISDR) (2006).

In terms of disaster risk management good practice, an effective SDS early warning system uses a *whole of community* approach (National Weather Service, 2018). In this approach, the actions by all stakeholders, especially at-risk and otherwise affected populations, are incorporated into a single approach to ensure that warnings are provided in a timely manner and that appropriate actions are taken to reduce or avoid negative impacts. An integrated process for defining, establishing and managing early warning systems requires the involvement of a wide range of stakeholders (see **Box 17**).

Box 17. Early warning stakeholders

A range of stakeholders in the forecast and warning process have important roles in developing, disseminating and using the SDS warning information. These include:

- specific at-risk groups that could experience significant negative health or other impacts from SDS
- regional forecast centres, including SDS forecasters, modellers and researchers
- national meteorological and hydrological services (NMHS), including forecasters, modellers and weather education specialists
- geological services or surveys, environment authorities and other national technical agencies and national alerting authorities
- national disaster management authorities (NDMA) and subnational counterparts, including planners, early warning system managers, response managers and trainers
- telecommunications officials, including technicians focused on system reliability and message management (including targeting messages to specific locations or audiences)
- health authorities and hospitals, including health specialists, facility managers, patient managers and emergency health care providers
- transport system management authorities (air, land, sea), including planners, maintenance crews and police (this should be separate under public safety or similar grouping) to ensure safety during SDS
- the media, including radio, TV and the Internet, as well as those working through these systems (for example, news readers, presenters, bloggers, etc.)
- agricultural and livestock producers, including agronomists, livestock specialists and infrastructure managers, to minimize SDS-related losses
- the private sector (businesses, industry and services, etc.), including those that can be affected by high airborne sand or dust loads, including high precision or low contamination production facilities and food preparation and sales
- education providers, including teachers providing education on SDS and school directors taking action to ensure student safety during SDS
- community welfare or care groups, which focus on assisting those more likely to be affected by SDS, including civil society organizations, non-governmental organizations and volunteers
- international (regional and global, inter-governmental and non-governmental) organizations.

Operationally, an SDS early warning system is based on an overall warning plan, which includes sources of information and analysis, dissemination methods and standard operating procedures (SOPs) to ensure warnings are received in a timely manner. Such plans are complemented by subplans for specific sectors (for example, health) and specific facilities (such as clinics) or specific purposes (such as road safety). The planning and overall coordination of the warning process is usually led by the national disaster management authority (NDMA) or similar agency, with some countries decentralizing part of these responsibilities to the subnational level.

In some countries, the national meteorological and hydrological service (NMHS) may be involved in warning dissemination in coordination with the NDMA.

These NMHS-generated warnings can be issued by local offices based on local near-real-time assessments of warning needs.

The effectiveness of SDS early warning systems and plans is judged not only by the sophistication of the SDS forecast and modelling. Rather, success is also based on how well individuals at risk from SDS take action to avoid or reduce the impact of the SDS. The people-centred, impact-focused approach takes forecast and warning data and combines these with vulnerability and exposure data in order to assess potential impacts and yield practical actions to reduce the impact of SDS on individuals, livelihoods and society as a whole.

Box 18. SDS warning and the Sendai Framework

The overall people-centred, impact-focused concept of early warning systems is reflected in three priorities for action of the **Sendai Framework for Disaster Risk Reduction 2015–2030** (United Nations, 2015):

- Priority 1: Understanding disaster risk, which is addressed through the work on disaster risk knowledge (upper left box in **Figure 44**).
- Priority 2: Strengthening disaster risk governance to manage disaster risk, which is addressed by focusing on coordination and partnerships, improving the effectiveness of the overall early warning system at all levels and across stakeholders, and having feedback mechanisms in place to allow for the system to improve over time.
- Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction, which is addressed through building, maintaining and strengthening "people-centred multi-hazard, multisectoral forecasting and early warning systems" (Ibid, p. 21), especially elements three (warning dissemination and communication) and four (preparedness and response capabilities) (see **Figure 44**).

In addition, improving SDS early warning systems contributes to achieving global target G "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030" of the **Sendai Framework** (UNDRR, 2018, p. 155), to be reflected through respective monitoring and reporting within the **Sendai Framework Monitor** tool (see https://sendaimonitor.unisdr.org/).

10.4. Impact-based, people-centred forecasting and early warning process

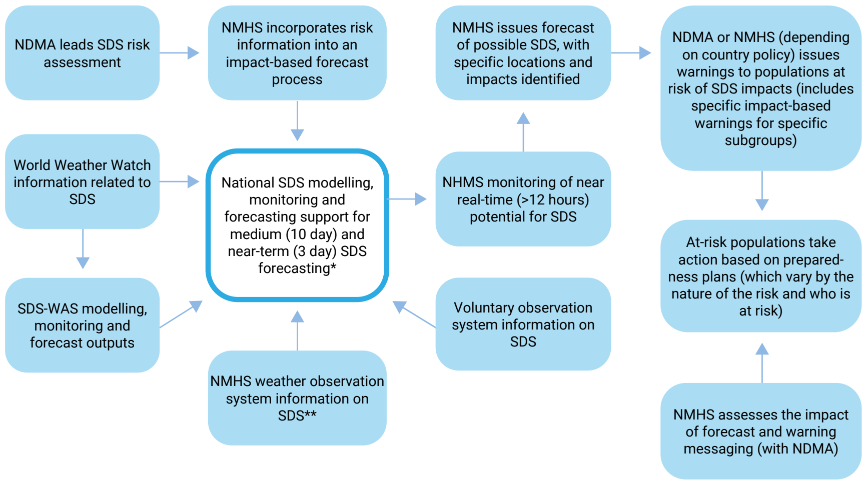
As discussed in **chapter 9**, SDS should be addressed through an impact-based, people-centred forecast and warning process. **Figure 45** graphically presents this process.

In the impact-based, people-centred forecast process:

- The NDMA leads the development and updating of SDS risk assessments (see **chapters 4**, **5**, **7**, and **6** for economic impacts).
- The NMHS integrates the risk assessment outputs into the forecasting and warning process.
- Results of assessments are integrated into the SDS modelling, monitoring and forecasting process, which also incorporates inputs from the WMO SDS-WAS modelling, monitoring and forecast process, as well as inputs from the NMHS observation system and voluntary SDS observations (see **chapter 9** on the Community DustWatch network).[1]
- The NMHS, or subnational branches, monitor SDS development on a near-real-time basis (over the next 12 hours).
- The NMHS, or subnational branches, issue specific SDS (impact-based, if possible) forecasts focusing on specific locations where SDS are expected.
- Depending on policies, the NDMA or NMHS issues warnings when justified by the available modelling, monitoring and observations.
- At-risk individuals take action based on the warnings and an understanding of the SDS impacts in order to avoid or reduce the expected impacts.
- After SDS events, the NMHS, together with the NDMA and other stakeholders, assesses the impact of the forecast and warning messages on whether at-risk individuals took action to avoid or mitigate SDS impacts. These assessments feed back to the system to improve the forecasting and warning process and product.

As described in **chapter 9**, if an NMHS does not have access to risk or vulnerability assessments, a pragmatic approach is recommended through which the NMHS and NDMA agree on impact matrices for SDS events and classify them in terms of the severity of the impact for various user groups.

1 See https://www.environment.nsw.gov.au/topics/land-and-soil/soil-degradation/wind-erosion/community-dust-watch



* Level of capacity varies between countries.
** National data provided to SDS-WAS via World Weather Watch.

Figure 45. Impact-based, people-centred forecast and warning systems for sand and dust storms

Table 22 provides an example of how the warning process can be integrated into tactical, strategic and research aspects of managing the impacts of SDS on specific sectors, in this case, agriculture. This type of planning can be integrated into SDS source mitigation (**chapter 12**) and impact mitigation and response (**chapter 13**) plans and procedures.

Table 22. Potential agricultural applications of an SDS warning system

Tactical (short term)	Strategic (long term)	Research
• Near-term warnings for agricultural communities to take preventive action: • harvesting maturing crops • sheltering livestock • strengthening infrastructure (houses, roads, crop storage).	• Improved SDS climatology for long-term planning for agricultural communities: • planning windbreaks and shelterbelts (direction, size, etc.) • planning for infrastructure and crops • post-storm crop damage assessments.	• Forecasting locust movement. • Improving soil/wind erosion and land degradation models. • Forecasting plant and animal pathogen movement and the relationship of SDS to disease outbreaks. • Archiving SDS warning system products for forensic use.

Source: Stefanski and Sivakumar, 2009

10.5. Authority to issue forecasts and warnings

There is a significant distinction between:

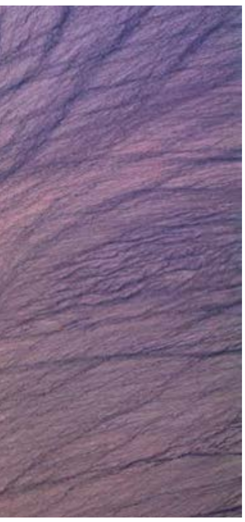
- forecasts, which include details of weather and atmospheric dust conditions and how they may change, and
- warnings, which are issued by a mandated authority and intended to trigger specific (compulsory or voluntary) actions and legal authorities, for example, requiring that facilities close or traffic be stopped.

It is important to note that forecasts may include alerts or watches and may be issued by the same authority (such as an NDMA) that issues warnings.

Due to the difference between forecasts and warnings, clarity is needed. In terms of plans and procedures, there should be a policy defining who has the authority to:

- issue forecasts, alerts and watches
- issue warnings
- order actions based on these warnings, such as closing facilities, restricting travel or implementing emergency contingency plans.

How forecast or warning information is provided to the public can vary between countries. In some cases, written-text watches and warnings are the norm, while in other countries, colours or numbers may be used to indicate the significance of information about hazard events. Understanding the warning mechanisms and terminology used by authorities and how it relates to decisions taken when a warning is received is an important component of an SDS early warning system.



While forecasts are normally provided by an NMHS, the authority to issue official warnings may rest, for example, with the:

- NMHS, based on established protocols, SOP and warning plans, with additional information on actions to be taken
- NDMA, which receives forecasts and warnings from the NMHS and then retransmits these with or without additional information, based on emergency response plans
- Office of the Prime Minister or President, when authority to initiate the legal authorities associated with warnings rests with these officials
- state commissions charged with emergency management, having the statutory authority to provide warnings and manage disasters.

It should also be noted that in many countries, disaster risk management is delegated to the subnational (province, state) level, with the NDMA playing a supporting role. In these cases, it may be the head of the state or province, the head of the provincial or state disaster management office or another official, such as a senior police officer, who has the authority to issue warnings. Subnational warnings may be based on information from subnational NMHS offices with a capacity to generate forecasts or on information provided by a centrally located forecast office, usually the national NMHS office.

In addition, disaster management authorities at the national, provincial/state or county/city administrative levels may use commercial forecasting services and other services (such as social media) for additional localized information on which to base localized warnings. The use of commercial services does not replace the NMHS, but should provide a level of local detail which may not be available from a NMHS.

In addition to NMDA and NMHS warnings being issued, specific sectoral warnings may also be issued by various authorities, including aviation, road transport, health and education, based on forecasts of the NHMS or other technical agencies. Public authorities and the private sector can also use commercial forecast services to anticipate and prepare for hazard events, issue internal warnings and alter standard practices based on warning and response plans.

To summarize, because the SDS warning process can vary considerably between countries, the following questions need clear answers:

- Who has the mandate and authority to issue forecasts, alerts, warnings or watches?
- Who has the legal authority to issue warnings?
- Who ensures that a warning is acted upon? The parties responsible for ensuring that warnings are followed can be different from the party which issues the warning. For instance, while it may be the NMHS that issues a warning, the police may have the authority to take action, such as restricting traffic, based on the warning.
- To whom does the NMHS or subnational offices provide forecasts and warnings and how?
- How can the NMHS and NDMA ensure that warnings are issued in a timely manner?

10.6. Warning plans and mechanisms

The need for clarity on the roles and responsibilities for forecasting and issuing warnings is usually addressed through detailed planning, resulting in plans and procedures for forecasts and warnings. In general, forecast plans are developed internally by the NMHS, with the development of warning plans led by the NDMA (if there are separate forecast and warning authorities in the country).

However, due to the end-to-end and overlapping nature of these plans and a need for forecast and warning authorities to work collaboratively, a single severe weather forecast and warning plan can be considered good practice. Such forecast and warning plans also need to involve other stakeholders, as summarized in **Box 17**.

Warning plans need to specifically consider the mechanisms that will be used to disseminate warnings. The general concept is that every at-risk individual who should receive an SDS warning is to be contacted through at least two warning mechanisms (see **chapter 10.8** on the process by which people react to warnings).

Common mechanisms for warning dissemination include print media, radio, TV, the Internet (including emails, social media and warning websites) and mobile phone messaging. Sirens and traditional face-to-face communication are also still important mechanisms. WMO provides guidance on disseminating and communicating SDS warnings. See https://public.wmo.int/en/our-mandate/focus-areas/natural-hazards-and-disaster-risk-reduction/mhews-checklist/warning-dissemination-and-communication. Which includes information that can be adapted for use by a NMHS or another authority that disseminates and communicates SDS warnings.

Redundancy should be built into early warning systems to address the risk that any warning mechanism may fail. This redundancy is both for the mechanisms used to warn (for example, sirens and radio both being used to issue warnings) and for the communication systems which link those issuing the warnings to specific warning mechanisms (for example, two ways to trigger a warning siren).

Under a multi-hazard warning approach, SDS warnings would generally be sent out through the same warning systems used for other hazards. This would increase the frequency with which warning systems are used and allow for more frequent verification that a multi-hazard warning system is working as expected.

10.7. Warning verification

Once warning messages and systems are developed and functioning it is necessary to verify both the accuracy and usefulness of the messages being delivered as well as the effectiveness of the system. This can be done in two ways:

- Message and system testing: This process involves testing messages with possible target audiences to verify that the messages result in the intended actions. This verification can be done through focus groups, simulation exercises or surveys (including commercial survey or feedback services). The feedback on the messages and their dissemination allows for the content of messages to be adjusted to improve the mechanisms' results.
- Post-event review: This process is carried out after an actual SDS event and involves asking those who should have received warning messages to review the usefulness and effectiveness of the messages they received (if they were received). This is usually conducted through some form of survey, the results of which helps to improve the forecast and warning system, including the formulation and dissemination of alert and warning mechanisms.

The importance of verifying warnings should not be underestimated. Without this feedback, an NMHS, NDMA or other parties involved in the warning process could find it hard to know whether the warnings issued helped people to avoid or mitigate the impact of SDS. Identifying whether, how and why warnings resulted in protective actions can improve warning messaging and dissemination, which in turn should increase the likelihood of individuals receiving warnings to take protective actions.

10.8. Warning education

For warnings to be successful, it is crucial that those receiving the warning understand the information provided and the corresponding actions to be taken to reduce SDS impacts in both the short term and long term, acting and adapting their general response to warnings as necessary. Warning education processes involve two aspects:

- understanding how and why warnings are or are not acted upon by those who receive them, and
- implementing a campaign to increase and sustain the knowledge of those receiving warnings so that they can take the appropriate action when warnings are received, thereby triggering longer-term and systematic behavioural changes.

The first point is of critical importance. If a warning is issued and not used, then it has no value. As summarized in **Emergency Alert and Warning Systems: Current Knowledge and Future Research Directions** (National Academies of Science, Engineering, and Medicine, 2018, p. 20), individuals who receive a warning message go through a process of:

- understanding whether the message is relevant to the person receiving it
- determining whether the warning is real or not
- personalizing the message as something for which action is needed
- deciding whether action needs to be taken
- confirming whether the information is correct and actions should be taken.

Unless warning messages and work to prepare people for warning messages take these points into account, it is unlikely that warning messages will be fully effective. The role of a continual education campaign is twofold:

- Educating those receiving a warning helps them move through the five aforementioned steps. If an individual is aware of the types of warnings that may be issued, the typical content of the messages, the expected or recommended action to be taken following a warning and how to confirm the veracity of messages and actions (if they are needed), then they will complete the five-step process quicker and with more certainty.

- Building the knowledge of populations at risk from SDS about these phenomenon and how they can impact society, along with the measures that can be taken to address their impacts. This knowledge-building needs to be an ongoing process for three reasons:

    1. A knowledgeable population is a prepared population.
    2. At-risk populations are constantly changing in terms of numbers, the composition of vulnerable groups and location.
    3. The means that a population may have to address SDS impacts can change over time. An ongoing education process can influence individuals, families, government services, businesses and others to improve the level of protection from and resilience to SDS. People and society need to know how to reduce the impacts of SDS before they can take action. Some risk reduction measures should be taken long before warnings are received.

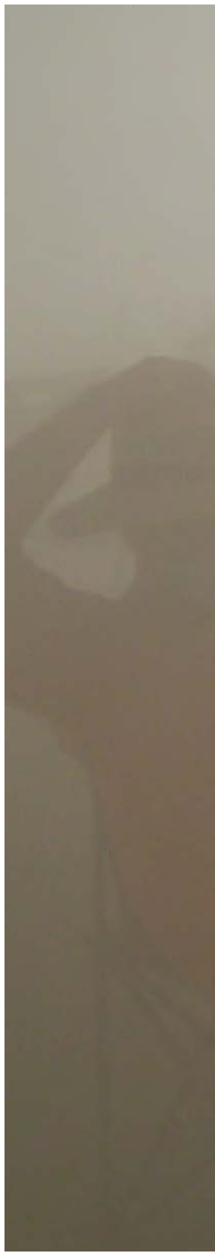
10.9. Integrating forecasts and warnings into preparedness

Chapter 13 discusses preparing for and mitigating SDS. Within the preparedness process, SDS forecasting and warning have four key roles. First, understanding the nature of SDS – which involves developing data sets, modelling and analysis needed to make the forecasts – creates the basis for understanding SDS as a hazard for which preparedness is needed. This understanding provides input into SDS management plans and procedures, including source and impact mitigation.

Second, the technical process and procedures for transforming information on SDS into a forecast lead to a result which does, or does not, trigger a warning. In other words, the content of a forecast can tell individuals to be prepared for SDS or can inform them that there is no need for concern.

Third, forecasts can trigger warnings, based on established warning criteria/ thresholds, plans and procedures. While a forecast can indicate a possible need to prepare for SDS (or not), the warning generated by a forecast triggers a set of actions to reduce the impact of SDS (see **chapter 13**). This triggering process is at the core of the impact-based forecasting and warning concept and is what activates short-term plans to reduce SDS impacts and hasten recovery.

Finally, the process of educating those at risk about SDS so that warnings can be effective (**chapter 10.8**) not only improves capacities to respond once the warning has been received, but also improves the level of individual and societal preparedness for SDS. This preparedness is important when SDS threats are imminent, but can also result in those at risk taking additional actions before a warning is issued or received in order to reduce the actual impact of SDS. The development of an effective warning system therefore improves preparedness and also reduces risk.



10.10. Conclusions

SDS forecasts and warnings are important to reduce the impact of these hazards on individuals, communities, organizations and society as a whole. For effective warnings that lead to protective actions, an SDS warning system needs plans that bring together the forecast capacities of an NMHS and the warning and response capabilities of an NDMA into a common plan.

These plans need to be clear on who is responsible for issuing warnings, how these warnings are to be issued and what information the warnings should contain. In general, following the people-centred, impact-based forecasting approach, warnings should include information about specific expected impacts of forecasted SDS, along with specific actions to address these impacts which also detail specific locations if possible.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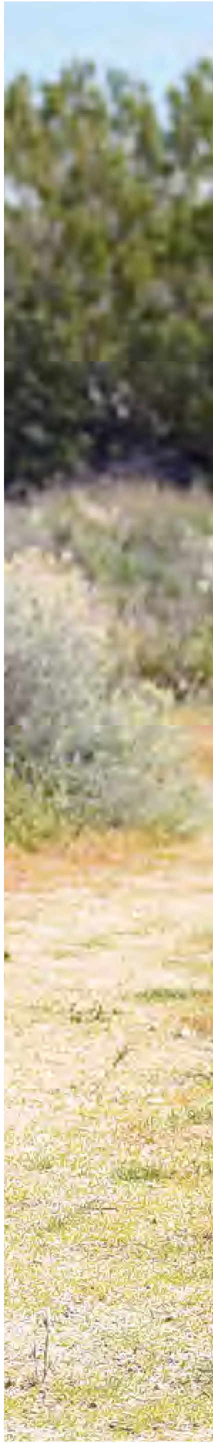

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11. Sand and dust storms and health: an overview of main findings from the scientific literature

Chapter overview

The chapter provides an overview of research into the health impacts of sand and dust storms (SDS). Most studies of SDS and health linkages have been conducted in Asia, Europe and the Middle East, with studies severely lacking in West Africa. Important issues in understanding SDS health impacts include: (1) the characterization of dust exposure of individuals and populations, which can be done in different ways; (2) the availability of health data is a challenge in many areas affected by SDS; and (3) even if exposure and health data are available, the method used to distinguish between dust storms and days affected by dust, along with the design of epidemiological studies, vary greatly, making it difficult to compare results from different studies.

Many health outcomes, both for mortality and morbidity, mainly focus on the short-term effects of SDS and have identified an increased risk of cardiovascular mortality and respiratory morbidity, including asthma. There is a lack of studies on the long-term effects of SDS, which means that estimates of the impact and burden of SDS are yet to be fully developed.

11.1 Introduction

This chapter will briefly discuss issues related to exposure to sand and dust storms (SDS), along with their health effects and impacts.
It should be read together with **chapters 12** and **13**.

Arid and semi-arid regions are the main global source areas for airborne mineral dust. These source areas comprise a third of the Earth's land surface, with some 2 billion people exposed daily (Safriel et al., 2005). At the same time, SDS have a significant impact over areas thousands of kilometres away from source areas (Ginoux et al., 2012; Prospero et al., 2002), carrying anthropogenic pollutants (Mori, 2003; Rodríguez et al., 2011) as well as microorganisms and toxic biogenic allergens (Goudi, 2014; Griffin et al., 2001; Ho et al., 2005).

According to the Intergovernmental Panel on Climate Change (IPCC), SDS will have potentially harmful health effects in the future (Intergovernmental Panel on Climate Chane [IPCC], 2019). SDS are therefore a challenge for the health system (Allahbakhshi et al., 2019) and have received increasing attention in recent years in terms of their impact on human health.

To date, there are no studies on the long-term health effects of SDS, which are needed to inform on the overall impact of such events on health. This chapter therefore presents the current evidence available, derived from existing short-term epidemiological studies from affected areas which suggest potential health effects of SDS (de Longueville et al., 2013; Hashizume et al., 2010; Karanasiou et al., 2012; Zhang et al., 2016).

The impacts of SDS and desertification are also related to well-being and social issues, though there are few available studies on this aspect (Adeel et al., 2005; World Health Organization [WHO], 2006), which is considered to be outside of the scope of this chapter.

11.2 Health effects of SDS

The health effects of SDS depend on where human populations are located in relation to SDS source areas, the downwind direction of dust transported from them and the length of exposure (Goudie, 2014). The populations most susceptible to suffering from the short-term effects of suspended particulates are considered to be older persons, individuals with chronic cardiopulmonary disorders and children (Goudie, 2014).

Previously published reviews, systematic or not, reported inconsistent results across studies and geographical regions (de Longueville et al., 2013; Hashizume et al., 2010; Karanasiou et al., 2012; Zhang et al., 2016). These reviews identified and summarized evidence from at least 45 epidemiological studies published between 1999 and 2014, predominantly on the short-term health effects of SDS. A potential limitation in the literature is the lack of studies conducted on the long-term health effects of SDS.

The health outcomes more frequently studied include: (a) daily mortality by all-natural causes and specific causes; (b) cardiovascular and respiratory issues; and (c) morbidity as documented in hospital admissions and emergency room admissions/visits, mainly for cardiovascular and respiratory issues, including asthma and chronic obstructive pulmonary disease (COPD) (see **Table 23**). Overall, the four reviews (de Longueville et al., 2013; Hashizume et al., 2010; Karanasiou et al., 2012; Zhang et al., 2016) had similar conclusions, suggesting that potential health effects linked to SDS may increase cardiovascular mortality and respiratory hospital admissions.

Table 23. Health outcomes investigated in epidemiological studies

Mortality	• All-natural cause mortality • Cardiovascular diseases • Respiratory diseases
Morbidity	• Cardiovascular diseases • Respiratory diseases (including asthma, COPD and pneumonia) • Coccidioidomycosis • Dermatological disorders • Conjunctivitis • Meningococcal meningitis • Allergic rhinitis
Other	• Pregnancy outcomes

Source: Adapted from Goudie, 2014 and Querol et al., 2019.

Other more specific morbidity outcomes have also been considered, although to a lesser extent, including: (a) cardiovascular-related outcomes (stroke, ischaemic heart disease, heart failure, myocardial infarction); (b) acute coronary syndrome and out-of-hospital cardiac arrest; and (c) respiratory-related conditions (pneumonia and upper respiratory tract infection). Allergy (daily clinical visits for allergic rhinitis) and infectious diseases outcomes (daily clinical visits for conjunctivitis and diagnosed cases of meningococcal disease) have been studied, but only occasionally.

Furthermore, just a few individual case-series (panel) studies have evaluated daily respiratory symptoms and peak expiratory flow of patients with asthma. None of the published studies considered deaths or injuries resulting from transport accidents occurring during SDS.

The published studies differed in terms of settings, assessment methods for SDS exposure, lagged exposures examined, and epidemiological study designs applied. Moreover, none of the previous reviews, systematic or not, attempted to assess the quality of the evidence across the published studies.

For this reason, the World Health Organization (WHO) decided to systematically synthesize the evidence on the health effects of SDS, accounting for the relevant desert dust patterns from source areas and emissions, transport and composition (Tobías et al., 2019a; Tobías et al., 2019b). This systematic review will be the first one to retrieve and evaluate published studies on the health effects of desert dust following a standardized protocol for data collection and reporting of findings. The results of this systematic review will provide evidence to fill the knowledge gap of the health effects of desert dust and may help develop appropriate preventive measures for dust episodes (WHO, in preparation).

11.3 Exposure to SDS and their health impacts

Desert dust can be transported for hundreds of kilometres and its natural composition can be affected by several human sources (Mori, 2003; Rodríguez et al., 2011), making the distinction between natural and anthropogenic particulate matter (PM) sources difficult to assess for the health effects of SDS. Recently, Querol et al. (2019) critically reviewed the exposure metrics for SDS commonly used in epidemiological studies.

Desert dust can be defined as a binary exposure, comparing the occurrence of the health outcome between days with and without a desert dust event. This exposure metric for SDS has mainly been used in studies conducted in eastern Asia (Hashizume et al., 2010; Tobias et al., 2019b).

These studies consistently found excess risks on desert dust days, especially for cardiovascular mortality (1.6 per cent) and respiratory morbidity (6.8 per cent) (Tobías et al., 2019b). Despite the intuitive design, these studies are highly dependent on the methodology to identify dust events and do not provide information on the dose-response relationship between SDS exposure and the health outcome.

The studies conducted in southern Europe have mostly considered daily PM concentrations as the main exposure, evaluating whether the health effects of PM differed between days with and without dust events (Karanasiou et al., 2012; Tobias et al., 2019b) by considering the dust binary exposure as an effect modifier of the link between PM and health.

The hypothesis underlying this approach is that it is not only PM from anthropogenic sources that is related to adverse health effects, but also particles originating from natural sources, especially desert dust advection from arid regions. Most of the studies found consistent evidence of larger effects of PM with a diameter of less than 10 µm (PM_{10}) and a coarse fraction ($PM_{10-2.5}$) on cardiovascular mortality during days with dust (increasing the risk of mortality by 9.0 per cent for a rise of 10 mg/m^3) than without dust events (2.1 per cent), and similarly for respiratory morbidity (13.8 per cent and -2.4 per cent, respectively). However, no difference was found for PM with a diameter of less than 2.5 µm ($PM_{2.5}$) (Tobías et al., 2019b).

The limitation of this approach is that PM is a mixture of natural and anthropogenic sources, even on dust days, which makes it difficult to attribute health effects to a specific source by classifying days according to the presence of a dust event.

Some studies have attempted to attribute daily PM exposure by separating desert and anthropogenic sources, showing that both sources were minimally correlated to each other and could be jointly analysed as independent risk factors for human health (Stafoggia et al., 2016). Under this approach, a multicentre study conducted in 11 cities of the Mediterranean region reported similar risk estimates for the anthropogenic and natural dust loads of PM_{10} on daily mortality and morbidity (Stafoggia et al. 2016).
A separate study conducted in the city of Barcelona, which considered anthropogenic loads of PM_{10} on days with and without dust events, reported that there was a larger risk of cardiovascular mortality for PM_{10} from anthropogenic contributions on dust days than non-dust days and that natural dust loads had a non-significant effect (Pérez et al., 2012). This approach is suitable to estimate concentration–response functions between desert and anthropogenic PM sources and health outcomes to assess the health impact of SDS.

However, studies conducted in East Asia, especially Japan, showed larger effects of Asian dust than suspended particulate matter on specific cardiovascular mortality outcomes (Kashima et al., 2012; Kashima et al., 2016) and ambulance calls for respiratory issues (Kashima et al., 2014).

Moreover, a relevant issue here is the difference between geographical regions, such as the Middle East, which has huge SDS events, and others such as southern Europe, where there are many small-scale dust episodes. In the former, it would not be particularly useful to investigate the independent effects of desert and anthropogenic sources, while in the later, this would be the most informative approach.

11.4 Estimating health impacts of SDS

Health impacts of air pollution are assessed by calculating their attributable proportion, which is the fraction of health outcomes resulting from air pollution of a population exposed to specific concentration levels. This attributed proportion is calculated using relative risks, or exposure–response function (ERF), from epidemiological studies. Other input data used to carry out an impact analysis include (1) the level of air pollution concentrations, (2) the population exposed, and (3) the baseline incidence of the health outcomes under consideration.

All epidemiological studies currently available only consider the short-term effects of SDS and provide estimates of the relative risk, or ERF, associated with PM mass concentration and not specifically with sand or dust exposure levels (for example, Stafoggia, 2016).

Unfortunately, epidemiological studies on the long-term effects of SDS are not available and ERFs related to any type of PM are used to assess long-term health impacts in populations exposed to SDS. This may potentially lead to very different results to those obtained had the ERFs been gathered using local data on exposure and health outcomes from SDS-affected regions.

To date, ERFs based on $PM_{2.5}$ studies carried out in the United States of America or Europe, which are locations with lower $PM_{2.5}$ concentrations and that likely have different $PM_{2.5}$ compositions, have been applied in SDS health impact assessments (Khaniabadi et al., 2017). Current estimates of the impacts should therefore be taken with caution as the use of these functions cannot be automatically generalized.

The quantification of desert dust-related health impacts has been published in few studies for short-terms effects (Khaniabadi et al., 2017; Renzi et al., 2018; Shahsavani et al., 2019; Viel et al., 2019) but rarely for long-term effects. Long-term exposure to desert dust, for example, was estimated to have generated 402,000 deaths in 2005 (Giannadaki et al., 2014).

The global fraction of cardiopulmonary deaths caused by atmospheric desert dust amounts to about 1.8 per cent, though in the 20 countries most affected by dust, in the so-called 'dust belt', this is estimated to be much higher at about 15–50 per cent (Giannadaki et al., 2014).

While in the city of Ilam in the West of Iran (172,213 inhabitants), the annual average and maximum PM_{10} value were 78 μg/m^3 and 769 μg/m^3 respectively, the maximum person-days of exposure were on days with concentrations between 40 μg/m^3 and 49 μg/m^3 (Khaniabadi et al., 2017). Considering a baseline of 1,250 and 48 for COPD and respiratory mortality respectively, about 338 and 26 cases were estimated as excess cases per year in Ilam (Khaniabadi et al., 2017).

Health impact estimates of SDS pose several challenges, including that:

- Exposure has to be thoroughly determined.
- Relative risks at very high levels of air pollution are to be extrapolated from risks measured for populations exposed to low-medium concentrations levels.
- Health data are often not available in the areas affected by SDS – for short-term exposures, health impacts should be designed by calculating impacts for dust days separately if the number of such days and corresponding concentrations are known.

In the case of long-term effects, yearly concentrations must be considered, though the share of PM due to desert dust compared with the total PM is only known approximately. Extrapolating the risk at very high levels of air pollution (for example, more than 50 μg/m^3 for $PM_{2.5}$) is difficult, as most of the epidemiological studies have been conducted in areas with lower $PM_{2.5}$ concentrations.

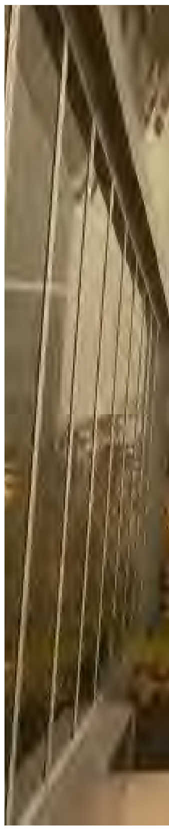
Available ERF extrapolation methods, such as integrated exposure risk functions (Burnett et al., 2014) have been developed for long-term exposures due to combustion-related $PM_{2.5}$. Their application for SDS might be questioned.

11.5 Developing a further understanding of health impacts and SDS

Although studies on SDS and human health are producing evidence on various health effects, there remain gaps in more clearly understanding how SDS and health impacts are linked.

To address these gaps, further study is needed in the following areas:

1. The design of studies on the effects of SDS on health should be improved, as most of the studies have used an ecological time-series approach, which cannot demonstrate causality. Dominici and Zigler (2017) proposed criteria to evaluate evidence of causality in environmental epidemiology that should be considered carefully for SDS studies, based on: (a) what actions or exposure levels are being compared; (b) whether an adequate comparison group was constructed; and (c) how closely these design decisions approximate an idealized randomized study.
2. PM exposure features should be better explored in epidemiological studies (Querol et al., 2019). For example, available modelling and meteorological tools, surface PM concentrations and $PM_{2.5}$/PM_{10} ratios could be used to define desert dust events and to quantify desert and anthropogenic sources of PM. The nature of major sources of dust and PM compositions also needs to be investigated in more detail, allowing for an assessment of the anthropogenic load of PM during SDS, and, if relevant, of the bio-aerosol load.



3. Studies of the health effects of SDS in and near hotspots, especially in West Africa and the Middle East, should be increased due to a lack of studies in these areas of significant SDS sources and impacts.
4. Surveillance and health data collection for populations in cities, regions and countries mainly affected by SDS need to be developed and/or improved, in particular for cardiovascular and respiratory diseases.

Health impact assessments of SDS should be further discussed and developed to tackle existing questions and challenges. There is a need to develop estimates for the long-term effects of SDS on human health. There is also a need to develop and explore appropriate methods (and/or ERF) to identify the fraction of diseases that can be attributed, based on causality, to SDS, to estimate the health impact and global disease burden associated with SDS.

SDS mitigation measures are essential to prevent negative health effects. Behavioural and technological interventions can mitigate the occurrence of SDS and exposure to desert dust. WHO will provide, within the current revision of the WHO Air Quality Guidelines (the main product for air pollution and public health), good practice statements on SDS.

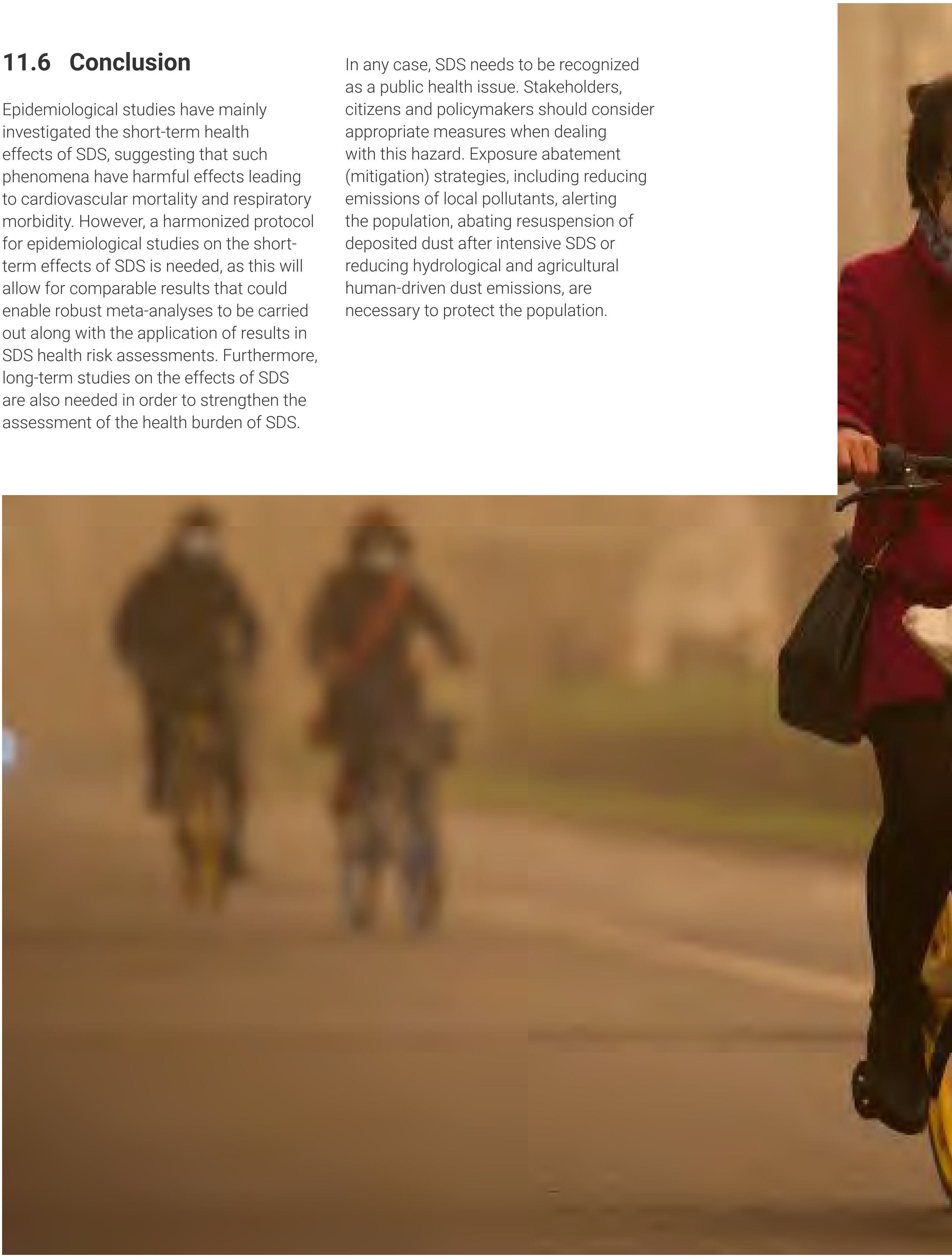
Reducing exposure is usually achieved through informing the population about a forthcoming event, minimizing outdoor activities that would have otherwise been carried out and cleaning streets after intense episodes to reduce urban resuspension of deposited dust. In the last decade, face masks and air filters have been the prominent technology to emerge, though their promotion for public health purposes is questionable (Rice and Mittleman, 2017). See **chapters 12** and **13** for further discussion.

LEO RAMIREZ—AFP/Getty Image

11.6 Conclusion

Epidemiological studies have mainly investigated the short-term health effects of SDS, suggesting that such phenomena have harmful effects leading to cardiovascular mortality and respiratory morbidity. However, a harmonized protocol for epidemiological studies on the short-term effects of SDS is needed, as this will allow for comparable results that could enable robust meta-analyses to be carried out along with the application of results in SDS health risk assessments. Furthermore, long-term studies on the effects of SDS are also needed in order to strengthen the assessment of the health burden of SDS.

In any case, SDS needs to be recognized as a public health issue. Stakeholders, citizens and policymakers should consider appropriate measures when dealing with this hazard. Exposure abatement (mitigation) strategies, including reducing emissions of local pollutants, alerting the population, abating resuspension of deposited dust after intensive SDS or reducing hydrological and agricultural human-driven dust emissions, are necessary to protect the population.




NOEL CELIS—AFP/Getty Image

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12. Sand and dust storms source mitigation

Chapter overview

This chapter reviews conceptual approaches and practical options to mitigate the sources of sand and dust storms (SDS) based on land degradation neutrality, sustainable land management, integrated land management and integrated water use management. Examples of SDS source mitigation measures are provided.

12.1 Introduction

This chapter explains how mitigating the source of sand and dust storms (SDS) can be integrated into national and/or regional planning, in line with global goals and initiatives, such as land degradation neutrality (LDN) targets, taking into account sustainable land management (SLM), integrated landscape management (ILM) and integrated water use management. The focus of the chapter is on reducing, to the greatest degree possible and particularly from anthropogenic sources, dust emissions and sand movements through measures focusing on:

- natural ecosystems
- rangelands
- croplands
- industrial settings, including mining, roads and construction.

The measures covered in this chapter can be divided into two groups, those which:

- reduce the generation of SDS at their source
- protect the environment, physical infrastructure and social and economic activities from sand and dust once they are in a state of movement.

These measures focus on:

- reducing wind speed in natural areas, rangelands and croplands
- controlling windblown sand and moving sand dunes
- implementing SLM, land-use planning and integrated landscape management approaches to integrate control measures into overall efforts to improve land use, sustainability and economic and social development.

Chapter 13 more closely considers measures that can be taken to minimize the impact of SDS as hazard events across different segments of society.

This chapter addresses the **United Nations Convention to Combat Desertification (UNCCD) Policy Advocacy Framework to combat Sand and Dust Storms** (United Nations Convention to Combat Desertification [UNCCD], 2017), focusing on source and impact mitigation, while providing avenues for monitoring, prediction and early warning, vulnerability reduction and resilience strengthening.

12.2 Sources and drivers of SDS

This section should be read together with **chapters 2**, **3**, **8** and **13**.

Although there is much uncertainty on the exact numbers, about 75 per cent of global dust emissions are derived from natural sources (Ginoux et al., 2012). Major dust sources are dominated by inland drainage basins or depressions in arid areas due to the wind-erodible nature of their surface materials and geomorphic dynamics (Bullard et al., 2011). However, natural ecosystems are increasingly subject to human pressures due to climate change and land-use and land-cover changes, which may intensify their importance as source areas in the future (Millennium Ecosystem Assessment, 2005).

Meteorological variables, such as wind velocity and low-level turbulence, are direct or indirect causing factors of SDS. Another causing factor of SDS includes soil-related factors, such as soil texture, soil moisture, soil temperature and vegetation cover, which at least in part is subjected to climate-related factors, including precipitation level and drought, as well as land degradation, both directly and indirectly.

There are strong reinforcing cycles, whereby removal of vegetation and unsustainable land management practices increase soil exposure to wind and increase soil susceptibility to erosion (Lal, 2001). Threats to natural areas include human intervention in hydrological cycles around ephemeral lakes, rivers or streams, as well as alluvial fans, playas and saline lakes in arid areas.

Such disturbances may accelerate desiccation, lower water tables, reduce soil moisture and reduce vegetation cover, thus exposing susceptible sediments to wind erosion (Gill, 1996). Hydrology disturbances around ephemeral lakes and playas are often due to demand for water resources for urban areas or irrigation.

Another contributor to playa desiccation is the development of roads and communication linear infrastructures that block or divert the inflow of drainage waters (Gill, 1996). Other causes resulting in accelerated wind erosion and dust mobilization include the removal of vegetation, loss of biodiversity and destruction of protective biological crusts in deserts due to vehicular traffic, tillage operations, loss in ecological connectivity and changes in animal migration patterns or exposure of erodible subsurface sediments.

Agricultural areas are a potential dust source. Unsustainable practices in the crop, livestock and forestry subsectors, such as the overuse of water or diversion of rivers for irrigation purposes, deforestation and forest degradation and intensive tilling or overgrazing, among many others, can lead to land degradation and directly contribute to higher risks of SDS.

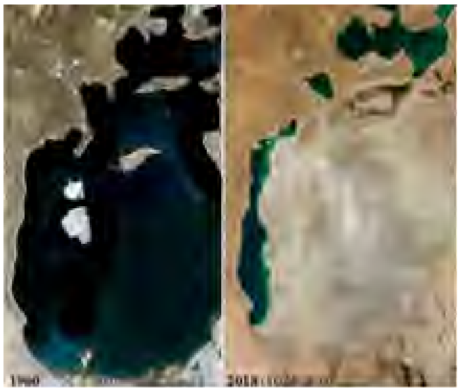
A failure to consider the potential for sensitive soil types to become a source of dust has been missed in the development of farming and livestock production.

Figure 46. Desiccation of ephemeral lakes due to human-made changes in hydrology

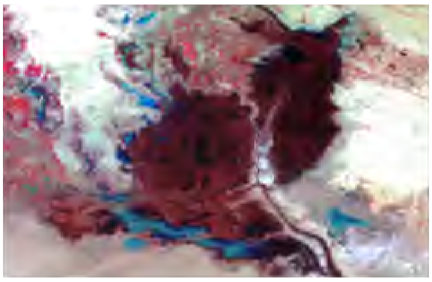
Source: San Antonio Express-News.

Figure 47. Receding shorelines in some inland waterbodies

Salton Sea, California, USA
Source: Johnston et al., 2019.
https://www.sciencedirect.com/science/article/abs/pii/S0048969719304164 and **https://ars.els-cdn.com/content/image/1-s2.0-S0048969719304164-ga1_lrg.jpg**



Aral Sea, Central Asia
Source: Krapivin et al., 2019.
https://www.mdpi.com/2306-5338/6/4/91/htm



1973 - 1976

2000

Marshes of Mesopotamia
(NASA Earth Observatory)
Source: https://earthobservatory.nasa.gov/images/1716/vanishing-marshes-of-mesopotamia

1998

2011

Lake Urmia, Iran
(NASA Earth Observatory)
Source: https://earthobservatory.nasa.gov/images/76327/lake-orumiyeh-iran

Examples include:

- the use of farming methods that led to a loss of vegetation (which previously reduced the potential for dust generation) and contributed to the Dust Bowl in the western plains of the United States
- overstocking of rangelands in the south-western United States, which caused region-wide transitions of grasslands to shrublands with low forage value (Finch, 2004)
- the East African groundnut scheme, which attempted to convert rangelands to land for mechanized peanut production agriculture (Herrick et al., 2016).

In Europe, wind erosion is a common process in the agricultural lands of most countries (Borrelli et al., 2016). The major risk factor for wind erosion and SDS in croplands, rangelands and forest areas is a decrease in vegetation cover, primarily because it increases wind velocity, exposes surfaces, usually makes surfaces less stable and enhances the risk of dust whirlwinds and reduces the trapping of sand and dust particles (Middleton, 2011). Vegetation also provides a natural mechanical barrier, controlling wind flows and reducing surface shear stress at the ground surface. Decrease in vegetation cover and any other management practices that remove or disturb organic layers at the soil surface (for example, ploughing) also increase surface exposure to wind. Organic inputs to soil are important for maintaining soil structure and biological activity, which increase effective particle size through aggregation as well as resistance to the detachment of soil particles by wind.

When individual land degradation processes occurring at the local level combine to affect large areas of drylands, it results in desertification. UNCCD defines desertification as land degradation in arid, semi-arid and dry subhumid areas due to various factors, including climatic variations and human activities (UNCCD, 2017).

Desertification is among the strongest large-scale drivers of SDS, as it reinforces wind erosion due to the development of degraded and exposed dry surfaces over large dryland areas with a long wind fetch. The combination of vegetation removal and unsustainable land management practices increases soil exposure to wind and therefore soil susceptibility to erosion.

Figure 48. Wind erosion in unprotected croplands – a major source of dust in dryland agricultural areas

Source: Canada, Ministry of Agriculture, Food and Rural Affairs.

Figure 49. Dust Bowl caused by unsustainable dryland agriculture and prolonged drought periods

Source: Pinterest.

Windblown sand and moving sand dunes can occur at wind speeds below those required to generate SDS. Despite this, they are considered in this chapter as they pose a hazard to:

- road and irrigation infrastructure, for example, covering roads, filling canals
- ground transport, by reducing visibility and damaging vehicles
- buildings and walls, through covering or banking up against structures
- fields, through covering or reducing the size of cultivatable areas.

Active, young or small sand dunes with a relatively rapid turnover of sand are unlikely to be major or persistent sources of dust because they contain little fine material (Bullard et al., 2011). The resulting dunes can, however, pose a risk to infrastructure, particularly roads and buildings, but also agricultural lands and gardens.

The disturbance of older dunes, on the other hand, will increase the risk of dust emissions. Any reduction in vegetation cover as a result of unsustainable harvesting, cultivation, grazing, burning or even drought, may lead to dune destabilization (Middleton, 2011).

Figure 50. Damage to infrastructure by moving sand dunes

Source: David Thomas.

Climate change can exacerbate the frequency and intensity of SDS as a result of changes in several drivers of these storms, including wind velocity, prolonged dry spells and reduced rainfall in source areas, which decreases soil moisture and vegetation cover. Dust generation and sand dune movement often increase in areas affected by periodic drought.

At the same time, land degradation also contributes to climate change (IPCC, 2019), due to the production of additional greenhouse gases, changes in surface energy balances and direct contributions of dust to the atmosphere, all of which are the result of changes in the condition of land in an SDS-vulnerable area (Arimoto, 2001).

Human-induced climate change is considered a driver in both natural and anthropogenic SDS generation. Climate change mitigation measures can help reduce dust emissions. Available options to address the impact of human-induced contributors to SDS are described in the 2014 report of the Intergovernmental Panel on Climate Change (IPCC).

12.3 Framing source management in the context of land degradation neutrality

12.3.1. Integrated approach for source management of SDS

The **Global Assessment of Sand and Dust Storms** (United Nations Environment Programme [UNEP], World Meteorological Organization [WMO] and UNCCD, 2016) identifies integrated approaches for SDS control in large areas, combining measures to cover different components of the landscape, including cropland, rangeland and deserts. An integrated approach is needed in potential source areas, in particular combining integrated landscape management with sustainable management of all landscape elements, while implementing proper land-use management including integrated land and water management and dust reduction from industrial sites, depending on the complexity of SDS drivers, factors and sources. Integrated landscape-level measures, including water resources, are especially important, given the transboundary impacts of SDS. Protective and rehabilitative measures in natural land, cropland and industrial settings for SDS mitigation should form part of integrated strategies for SDS source management using SLM and ILM.

SLM (**Box 19**) can be defined as "the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions" (Liniger et al., 2008). SLM practices reduce soil and land degradation by different driving factors, such as wind and run-off.

Best SLM practices are rather well documented, with many recorded, for example, in the World Overview of Conservation Approach and Technologies (WOCAT) database, which was created in the mid-1990s.[1] WOCAT continues to upload information, particularly on SLM technologies and adaption, through collaboration In this regard, the UNCCD Science-Policy Interface (SPI) technical report (Sanz et al., 2017) provides scientifically sound practical guidance for selecting SLM practices that help address desertification, land degradation and drought, climate change adaptation and mitigation, and for creating an enabling environment for their large-scale implementation considering local realities.

Improved SLM requires a better understanding of the interrelationships and coordination mechanisms linking ecological, social, cultural, political and economic dimensions by all stakeholders from local to international levels. Participatory planning approaches at the community levels and a cross-sectoral coordination development framework will also play a role towards managing land in a sustainable way (Alemu, 2016). Land suitability analysis and participatory land-use planning are necessary to choose the optimum practices for any given set of biophysical and socioeconomic conditions.

The greatest attention needs to be paid to ILM in potential source areas, combining sustainable management of all landscape elements, including integrated water management and the reduction of dust from industrial sites. ILM (**Box 20**) refers to long-term collaboration among different groups of stakeholders to achieve the multiple objectives required from the landscape, such as agricultural production, the delivery of ecosystem services, cultural heritage and values and rural livelihoods, among others (Scherr et al., 2012).

ILM supports integration across sectors and scales, increases coordination and ensures that planning, implementation and monitoring processes are harmonized at the landscape, subnational and national levels. Integrated water resources management is an important component of ILM and is especially relevant to SDS preventive measures.

By coordinating strategies and approaches and maximizing synergies between different levels of government, ILM can create cost efficiencies at multiple levels, including SDS mitigation. Given that ILM supports an inclusive, participatory process that engages all stakeholders in collaborative decision-making and management, it can also help empower communities. As a natural resource management strategy, ILM can enhance regional and transnational cooperation across ecological, economic and political boundaries.

1 See https://qcat.wocat.net/en/wocat/.

Box 19. Sustainable land management principles

The TerraAfrica Partnership (https://www.wocat.net/library/media/26/) presents three principles of SLM as well as principles for upscaling SLM:

SLM principle 1: increased land productivity

- Increase water-use efficiency and water productivity (reduce losses, increase storage, upgrade irrigation)
- Increase soil fertility and improve nutrient and organic matter cycles
- Improve plant material and plant management, including integrated pest management
- Improve microclimatic conditions

SLM principle 2: improved livelihoods and human well-being

- Support small-scale land users with initial investments, where there are often high initial costs and no immediate benefits
- Ensure maintenance through land users' ownership of SLM activities
- Consider cultural values and norms

SLM principle 3: improved ecosystems

- Prevent, mitigate and rehabilitate land degradation
- Conserve and improve biodiversity
- Mitigate and adapt to climate change (increase carbon stock above and below ground, for example, through improved plant cover and soil organic matter)

Principles for upscaling SLM

1. Create an enabling environment: institutional, policy and legal framework
2. Ensure local participation combined with regional planning
3. Build capacities and train people
4. Monitor and assess SLM practices and their impacts
5. Provide decision support at the local and regional levels to:

    - identify, document and assess SLM practices
    - select and adapt SLM practices
    - select priority areas for interventions

Box 20. Integrated landscape management

Five key elements characterize ILM, all of which facilitate participatory development processes. These are:

1. Shared or agreed upon management objectives that encompass multiple benefits from the landscape.
2. Field practices that are designed to contribute to multiple objectives.
3. Management of ecological, social and economic interactions for the realization of positive synergies and the mitigation of negative trade-offs.
4. Collaborative, community-engaged planning, management and monitoring processes.
5. The reconfiguration of markets and public policies to achieve diverse landscape objectives (Scherr et al., 2012).

Sayer et al. (2013) proposed 10 principles for ILM. A landscape approach seeks to provide tools and concepts for allocating and managing land to achieve social, economic and environmental objectives in areas where agriculture, mining and other productive land uses compete with environmental and biodiversity goals. These principles emphasize adaptive management, stakeholder involvement and multiple objectives:

1. Continual learning and adaptive management.
2. Common concern entry point.
3. Multiple scales of intervention.
4. Multifunctionality.
5. Multiple stakeholders.
6. Negotiated and transparent change logic.
7. Clarification of rights and responsibilities.
8. Participatory and user-friendly monitoring.
9. Resilience.
10. Strengthened stakeholder capacity.

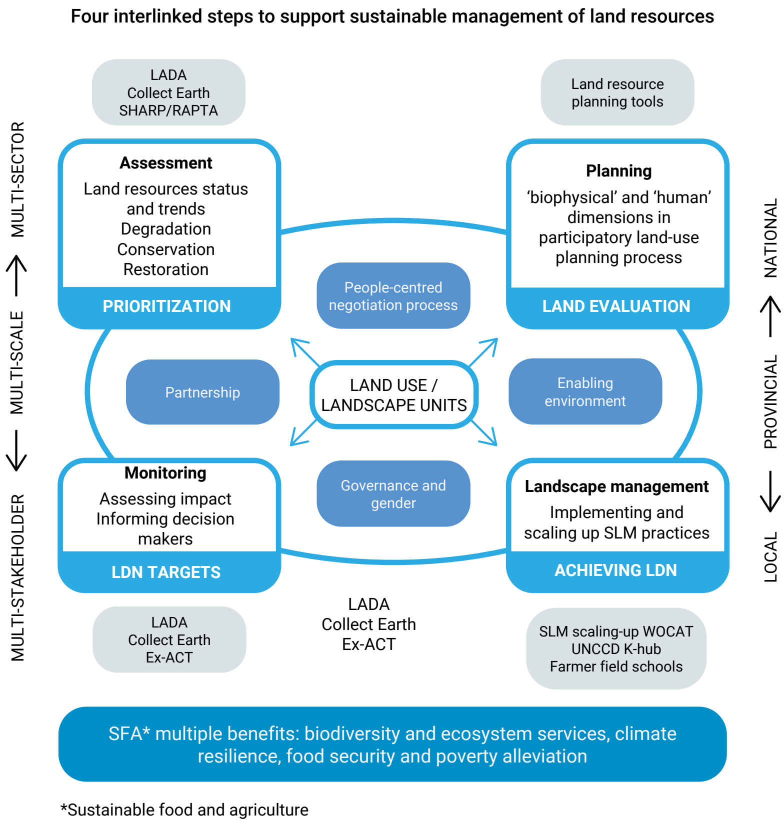


Figure 51. Interlinking steps to support sustainable land-use management

Source: Food and Agriculture Organization of the United Nations (FAO), 2018.

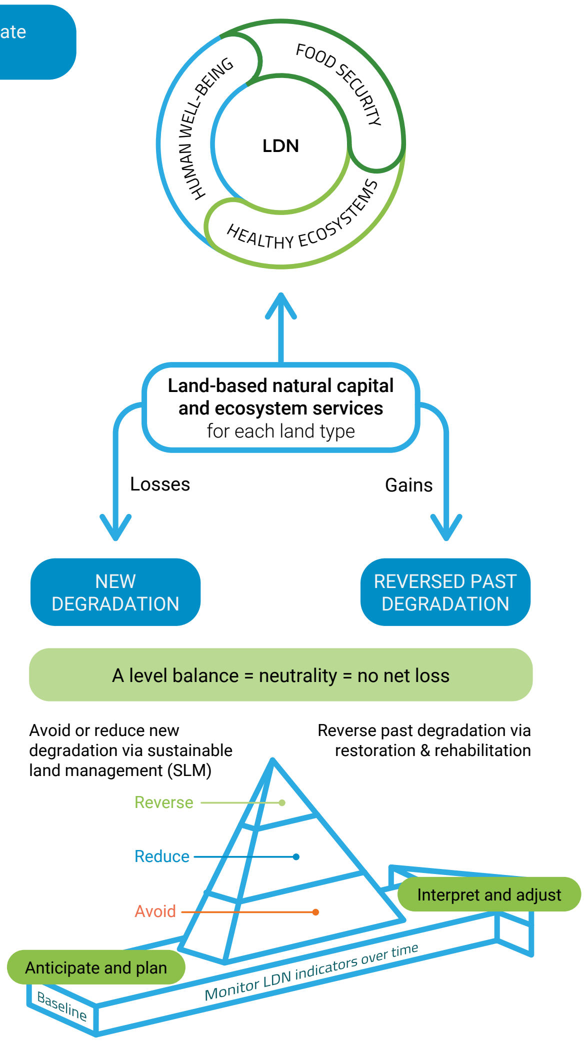


Figure 52. Conceptual framework for land degradation neutrality

Source: UNCCD, 2016.

Four interlinked steps are promoted to support sustainable land management: assessment, planning, landscape management through SLM implementation, and monitoring (**Figure 51**). These are indispensable components to scaling up SLM practices, which generate tangible positive impacts and support the achievement of sustainable management of natural resources and combating land degradation.

12.3.2. Integrating source management of SDS in the context of land degradation neutrality

LDN is adopted as SDG target 15.3.[2] The concept of LDN is designed to develop and implement policies promoting the rehabilitation and restoration of degraded land. It can provide a practical framework to develop and implement SDS source management strategies that take into consideration existing measures and approaches.

LDN can be achieved by avoiding land degradation and upscaling SLM and ILM practices. Restoration and rehabilitation measures of degraded land can greatly contribute to SDS source mitigation at the national and regional levels.

Measures to achieve LDN targets in SDS source areas can reduce the susceptibility of land to wind erosion, thus reducing the frequency and intensity of SDS. Reducing dust emissions and the impacts of SDS can better be achieved through the successful implementation of sustainable water use. SDS source management is directly and/or indirectly linked to the LDN indicators, namely land productivity, land cover/land-use change and soil organic matter.

Figure 52 illustrates the interrelationships among the major elements of the scientific conceptual framework for LDN.

- The target at the top of the diagram expresses the vision of LDN, emphasizing the link between human prosperity and the natural capital of land – the stock of natural resources that provides flows of valuable goods and services.
- The balance scale in the centre illustrates the mechanism for achieving neutrality, ensuring that future land degradation (losses) are counterbalanced through planned positive actions elsewhere (gains) within the same land type (same ecosystem and land potential).
- The fulcrum of the scale depicts the hierarchy of responses. Avoiding degradation is the highest priority, followed by reducing degradation and finally reversing past degradation.
- The arrow at the bottom of the diagram illustrates that neutrality is assessed by monitoring the LDN indicators relative to a fixed baseline. The arrow also shows that neutrality needs to be maintained over time through land-use planning that anticipates losses, plans gains and applies adaptive learning, where tracking allows for mid-course adjustments to help ensure that neutrality is maintained in the future.

The LDN conceptual framework (**Box 21**) emphasizes that the goal of LDN is to maintain or enhance the land resource base, in other words, the stocks of natural capital associated with land resources, in order to sustain the ecosystem services that flow from them, including food production and other livelihood benefits. The conceptual framework creates a common understanding of the LDN objective and consistency in approaches to achieving LDN. It has been designed to create a bridge between the vision and practical implementation of LDN through national action programmes by defining LDN in operational terms (UNCCD, 2016).

The conceptual framework applies to all types of land degradation so that it can be used by countries according to their individual circumstances. The framework provides a scientifically-sound basis to understand LDN in order to inform the development of practical guidance to pursue it and to monitor progress towards related targets.

2 See https://sustainabledevelopment.un.org/?menu=1300.

Box 21. Principles of land degradation neutrality

The LDN conceptual framework presents principles to be followed by all countries that choose to pursue LDN. The principles govern the application of the framework and help prevent unintended outcomes during the implementaton and monitoring of LDN. There is flexibility in applying many principles, but the fundamental structure and approach of the framework are fixed in order to ensure consistency and scientific rigour.

1. Maintain or enhance land-based natural capital.
2. Protect the rights of land users.
3. Respect national sovereignty.
4. For neutrality, the LDN target equals (is the same as) the baseline.
5. Neutrality is the minimum objective: countries may elect to set a more ambitious target.
6. Integrate planning and implementation of LDN into existing land-use planning processes.
7. Counterbalance anticipated losses in land-based natural capital with interventions to reverse degradation in order to achieve neutrality.
8. Manage counterbalancing at the same scale as land-use planning.
9. Counterbalance like-for-like (Counterbalance within the same land type).
10. Balance economic, social and environmental sustainability.
11. Base land-use decisions on multivariable assessments, considering land potential, land condition, resilience and social, cultural and economic factors.
12. Apply the response hierarchy in devising interventions for LDN: avoid–reduce–reverse land degradation.
13. Apply a participatory process: include stakeholders, especially land users, in designing, implementing and monitoring interventions to achieve LDN.
14. Reinforce responsible governance: protect human rights, including tenure rights, develop a review mechanism and ensure accountability and transparency.
15. Monitor using the three UNCCD land-based global indicators: land cover, land productivity and carbon stocks.
16. Use the one-out, all-out approach to interpret the result of these three global indicators.
17. Use additional national and subnational indicators to aid interpretation and to fill gaps for ecosystem services not covered by the three global indicators.
18. Apply local knowledge and data to validate and interpret monitoring data.
19. Apply a continuous learning approach: anticipate, plan, track, interpret, review, adjust and create the next plan.

Source: UNCCD, 2016.

12.4 Source mitigation measures – prevention

12.4.1. Overview

Measures to prevent SDS focus on reducing risks posed by the aforementioned drivers.

The protection of natural areas and the sustainable management of dryland forests, rangelands and croplands are critical preventive measures to counteract SDS, especially in areas where sediments or soils are sensitive to wind erosion.

Integrated landscape management is the optimal strategy, combining sustainable management of all the above landscape elements, including integrated water management.

Mapping sensitive source areas will help with the prioritization of areas for preventive action, using the criteria developed by Bullard et al. (2011), for example, for determining susceptibility to erosion based on geomorphology (see **chapters 2**, **6** and **8**).

Table 24. Preventive measures in rangelands and natural ecosystems

Objective	Control measures
Sustainable land and water-use planning around ephemeral lakes, rivers or streams, and alluvial fans, playas and saline lakes in arid areas	Prevent diversion of water Prevent devegetation of surrounding catchments Avoid/reduce disturbance of natural crusts (algal, lichens)
Manage vegetation in rangelands	Avoid overgrazing through reduced stocking rates or rotational and controlled grazing Avoid over-exploitation of trees and shrubs Reduce burning of grasses and plant litter Maintain perennial grasses
Protect vegetation in natural steppe, desert areas, and dune fields	Retain diverse vegetation cover Reduce fire risk Avoid/reduce disturbance of natural crusts
Fix sand dunes	Plant dead fences, grasses and shrubs

Source: Adapted from UNEP, WMO and UNCCD, 2016.

12.4.2. Natural areas and rangelands

Preventive measures in natural ecosystems and rangelands focus on vegetation and water management, as well as the sustainable management of livestock (**Table 24**).

In natural ecosystems, protection measures should aim to retain diverse vegetation, reduce fire risk and minimize disturbances of natural crusts by vehicular traffic. For example, disturbances of deserts can disrupt the natural vegetation patchiness, resulting in more connected pathways between bare soil patches, which provide channels for wind and water erosion as well as transport, thus leading to desertification (Okin et al., 2009).

Methods for controlling wind erosion and soil degradation in rangelands are often designed to reduce the pressure of grazing by excluding livestock from pastures either for short periods to allow the plants to mature and shed their seeds or for a certain number of years to allow degraded rangelands to fully recover.

Alternatively, reduced stocking rates could be introduced by placing a limit on livestock densities through the establishment of prescribed carrying capacities per hectare in areas where grazing is allowed (Middleton and Kang, 2017).

However, these types of rangeland management measures need to consider and ensure secure user rights as well as adequate incentives for rangeland users, supporting them in building organizational capacities and collective actions. There is increasing recognition that for sustainable rangeland management in drylands, location-specific, biophysical, social, cultural and economic factors at various temporal and spatial scales need to be taken into consideration (Vetters, 2004).

Various strategies can be implemented to manage the socioeconomic impacts caused due to the drying lakes and waterbodies, including SDS. For example, re-wetting or re-charging of waterbodies and establishing vegetation covers in dried lake beds can be considered in the context of SDS source mitigation, taking into consideration the specificity of local situations (Tussupova et al., 2020; Robinson 2018).

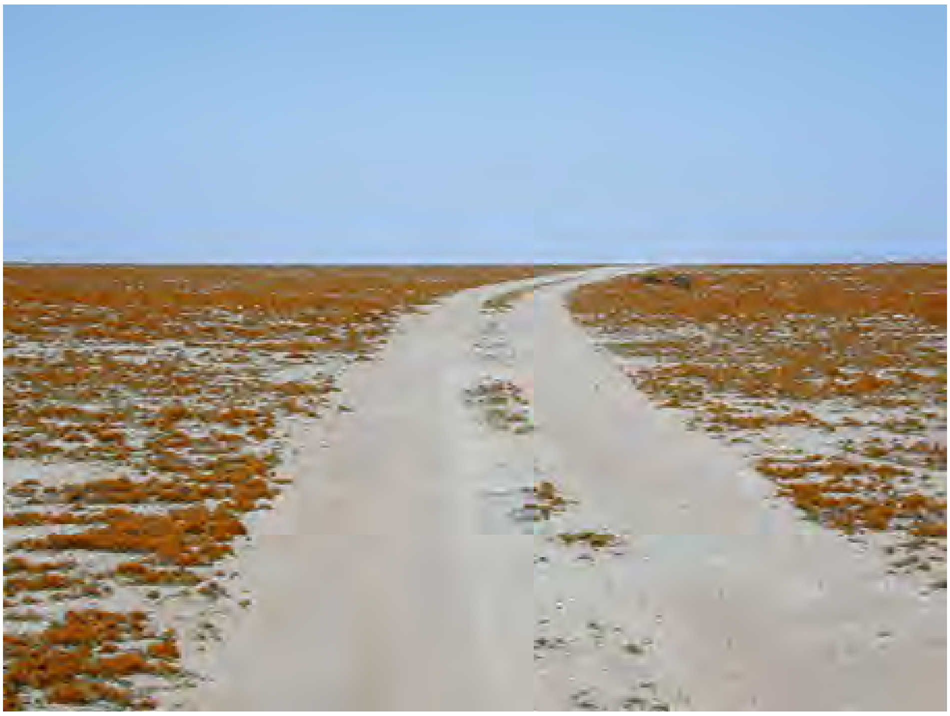


Figure 53. Mobilizing desert dust can be prevented by reducing damage to protective biological crusts in deserts by confining vehicular traffic

Source: Jennifer Lalley, University of Johannesburg.

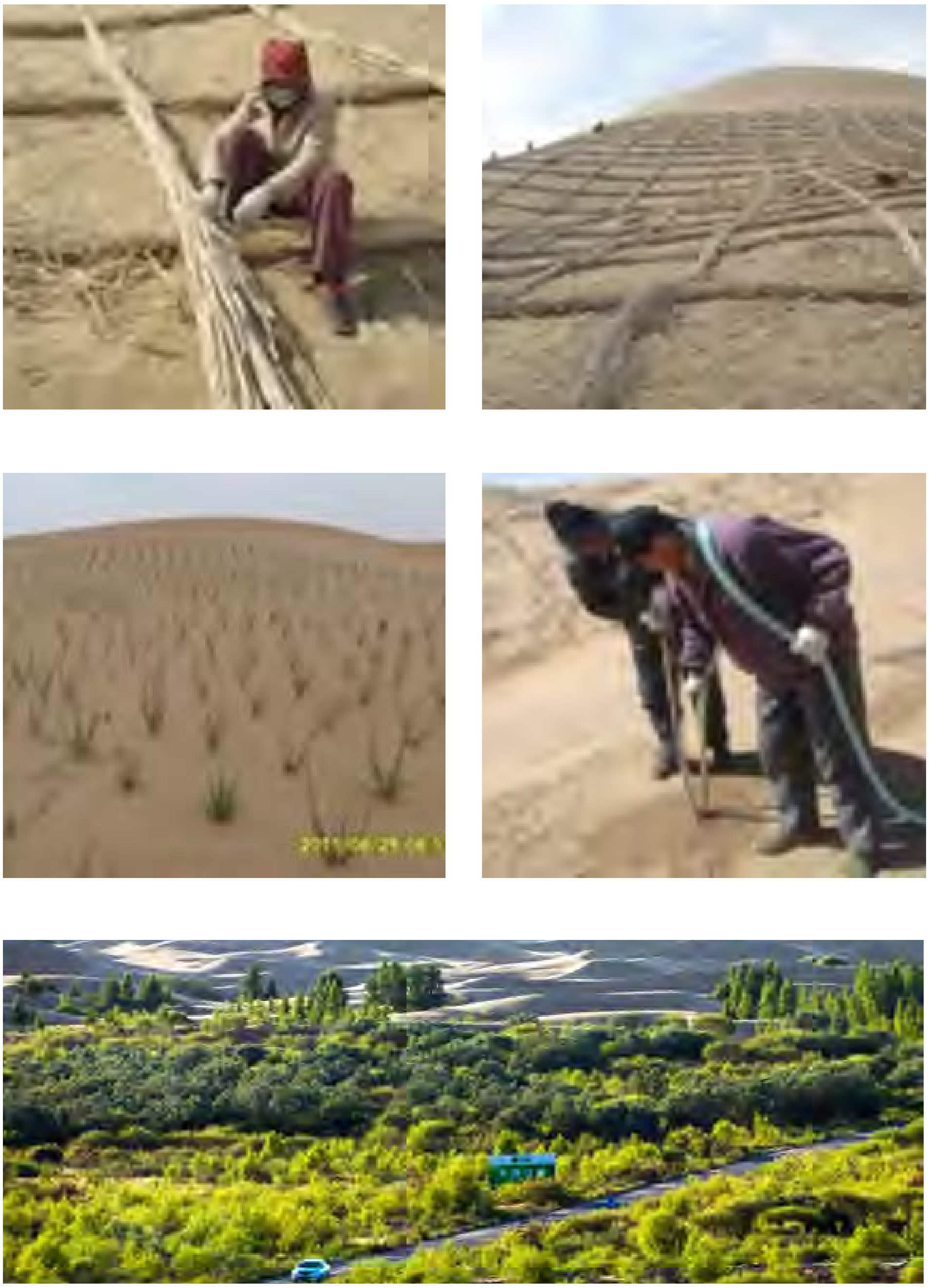
Figure 54. Vegetation management in rangelands protects soil from wind erosion

Source: Conservation International.

Remedial measures are generally too expensive to be practical except in situations where high-value assets are at risk. Such measures include returning stream flows to re-flood old lake beds, applying chemical surfactants, spreading gravels, irrigating to dampen the soil surface, implementing mechanical compaction and paving roads (Gill and Cahill, 1992).

However, there have been remarkable instances of degraded desert land being reclaimed and sand dunes being stabilized through revegetation (where water resources allow), despite the high labour requirements involved. One stabilization method involves laying out fences of straw and bundled shrub stems in a grid pattern across the land, before planting drought-resistant indigenous shrubs which are established using a water-jetting technique. After 25 years, this results in a protection belt, as seen in **Figure 55**, thus stabilizing sand dunes and preventing their impacts to roads, for example (UNEP, 2015).

Figure 55. Stabilization of sand dunes in the Kubuqi Desert, northern China



Source: UNEP, 2015.

12.4.3. Croplands

Strategies for controlling SDS in cultivated areas aim to reduce soil exposure to wind, decrease wind speed or minimize soil movement (**Table 25**). All wind erosion control measures (Mann, 1985; Yang et al., 2001) are relevant in controlling SDS.

Table 25. Measures to minimize wind erosion in cropland

Objective	Control measures
Reduce periods with little or no soil cover*	Adjusting the time of planting Relay cropping Crop rotation Reduced or no tillage
Reduce area with little or no soil cover	Inter-cropping Cover cropping/nurse crops Mixed cropping Strip cropping Surface mulching Reduced or no tillage Multi-strata systems Good crop management
Increase soil resistance to wind erosion	Increased input of organic residues through increased crop productivity, organic mulches, manures Reduced soil disturbance through limited or no tillage
Reduce wind speed within and between fields	Ridging Strip cropping Crop rotation Hedgerows Dead fencing (crop or tree residues) Linear planting of trees Scattered planting of trees
Reduce soil movement	Tillage practices that increase surface roughness

Note: * Soil cover is the degree to which soil is protected by vegetation, organic litter layers or mulch.
Source: UNEP, WMO and UNCCD, 2016.

The most fundamental measure is reducing soil exposure to wind by:

- protecting the soil with live or dead vegetation
- minimizing the time and area that soil has little or no cover, especially during dry periods or wind erosion seasons.

Various cropping, residue management and reduced tillage practices can help achieve this objective. In addition, roots of live vegetation act as a soil binding mechanism. Crop management practices that increase above-ground or below-ground inputs of organic residues to the soil, either through improved productivity or by returning a larger fraction of residues, will improve soil stability and resistance to detachment and erosion, by increasing the threshold velocity required for soil movement or by increasing surface roughness.

Conservation agriculture, for example, is recognized as an efficient method for reducing wind erosion losses. It aims to achieve minimal soil disturbance through reduced or no tillage, maximize residue cover on the soil surface and improve water use and soil fertility through inter-cropping.

Some agronomic management practices, such as mulching, for example, that increase crop vigour also reduce the time that soil is bare during the cropping season. Vegetation cover and soils can also be increased and stabilized respectively through various traditional soil and water conservation measures, which include water harvesting techniques, soil conservation bunds and organic manures (Biazin et al., 2012, Schwilch et al., 2014). Other good management includes factors such as the use of quality planting material, optimal plant density, appropriate soil and crop nutrient management and adequate pest and disease control.

Figure 56. Reduced and mulch tillage systems providing soil protection from wind erosion

Source: Paul Jasa - Extension Engineer, May 2018.

Figure 57. Windbreak protecting cropland in large field

Source: NRCS, 2012 - Field windbreak in northwest Iowa, by Lynn Betts

Adoption of agroforestry and silvopastoral systems, in which trees are integrated with agricultural land use, pasture and livestock, can also reduce the risk of SDS. Trees and shrubs can be planted around fields and homesteads, along roadsides, on soil conservation contours within fields and in riparian areas.

In dryland areas, scattered trees can play a significant role in protecting croplands. The use of biodegradable material and by-products, for example, from the cotton industry, provides opportunities to protect large areas (Young, 1989).

Figure 58. Scattered trees offering protection to cropland and livestock in a parkland system in Mali

Source: Gemma Shepherd, UNEP 2012

Figure 59. Zai pits hold water on the land to improve crop growth in poor or eroded lands

Note: Zai pits can help crops or other vegetation to grow in otherwise barren or unvegetated soils, for example, denuded dunes.
Source: CGIAR.

12.4.4. Industrial settings

Industrial sources of dust, such as mining operations, have specific options for preventing dust from being generated or leaving the site. These include various types of dust collection systems, water application (hydraulic dust control) to dry materials, physicochemical control of surfaces and cultivation of tailing dumps (Cecala et al., 2012).

Physicochemical methods may be used to stabilize tailing dumps using both natural materials and synthetic polymeric materials with structure-forming properties (Masloboev et al., 2016). Solutions of inorganic and organic natural cementitious polymeric materials and multi-component binding materials (polyacrylamide, liquid rubber, bitumen, etc.) are used as binding reagents.

Several studies (for example, Baklanov and Rigina, 1998; Amosov et al., 2014) have examined the effects of different factors and conditions on dust production from tailing dumps, including wind velocity, humidity and other meteorological parameters, material moisture content, the size and shape of particles, the efficiency of dust catching and the height and geometry of tailing dumps, as well as specific measures to reduce dusting, such as protective barriers. Numerical modelling studies have indicated that two-metre high protective barriers located on the leeward side of tailing dumps is effective in reducing levels of atmospheric pollution downwind (Melnikov et al., 2013).

Figure 60. Surface stabilization for dust control at an industrial site using soil binding agents applied by a hydroseeder

Source: Bender GmbH and Co.KG.

12.5 Protective measures

Physical protection of valuable assets, such as towns, infrastructure and irrigation schemes, are given in **Table 26**.

Table 26. Measures to protect valuable assets from sand and dust

Objective	Control measures
Restrict movement of sand and dust around valuable assets Stabilize sand dunes	Windbreaks around urban areas, along roads and other infrastructure Sand dune fixation with vegetation or chemical substances Agroforestry
Prevent sand accumulation	Aerodynamic methods, such as alignment of roads, removal of obstacles to wind and land shaping

A major challenge is to protect areas and infrastructure from unwanted dust and sand deposits from SDS. Reducing wind speed through tree planting, such as shelterbelts, around urban areas and infrastructure helps to trap dust and deposit sand outside these areas (Bird et al., 1992). However, impacts on lighter dust particles carried above tree height may be limited.

Wind erosion can blow sand and mobile sand dunes at wind speeds that are too low to generate SDS, but which pose an aeolian hazard (Wiggs, 2011). Measures to protect against this type of sand and dune movement are therefore relevant. Such measures tend to be associated with active dune fields and sand transport corridors in drylands where topographic depressions accumulate sand-sized material.
Urban areas and infrastructure, as well as farms established on the edges of such areas, become susceptible to windblown sand and moving sand dunes (Wiggs, 2011). Active dunes can migrate more than 15 metres per year, causing significant hazards to human activities (Al-Harthi, 2002).

There are various measures for controlling windblown sand and moving sand dunes, as summarized in **Table 27**. Examples of various types of fences used to protect the Qinghai-Tibet railway in China are given by Zhang et al. (2010). Various measures implemented to protect infrastructure in Kuwait are summarized by Al-Awadhi and Misak (2000).

Table 27. Measures to control windblown sand and sand dunes

Control measures	Examples
Windblown sand	
Enhance deposition	Ditches, fences, tree belts
Enhance transport	Streamlining techniques; creating a smooth texture over the land surface; erecting panels to deflect the air flow
Reduce the supply of sand upwind	Surface stabilizing techniques; fences; vegetation
Deflect moving sand	Fences, tree belts
Moving dunes	
Mechanical removal	Bulldozing
Dissipation	Reshaping; trenching; surface stabilization techniques
Immobilization through altering aerodynamic form	Surface stabilization techniques; fences

Source: Watson, 1985.


©Esin Üstün on Flickr, March 10th, 2015

Stabilizing sand dunes usually involves some form of primary temporary protection to reduce sand movement and aid the establishment of vegetation (FAO, 2010). Primary stabilization can be accomplished by stone mulching, wetting, chemical stabilizers, biological crusting or covering the ground with any other material, such as plastic sheets, nets and geotextiles, among others.

Fences of materials such as straw and tree branches are also frequently used, either in chequerboard or linear arrangements. More capital-intensive methods using sprays of petroleum emulsion products have been tested in Egypt, Kuwait and Libya for stabilizing sand dunes prior to establishing vegetation (Grainger, 1990; Ramadan et al., 2010) and are used to stabilize surfaces in some industrial settings.

The mitigation of SDS using a hybrid biological–mechanical system was shown to be cost-effective with an equivalent saving of 4.6 years of sand encroachment. The integrated biological–mechanical control system comprises two impounding fences (two-metre high, chain-link and slats fencing) situated 90–100 metres apart with three rows of drought-resistant trees (*Prosopis juliflora* and *Acacia etbaica*) in the middle section between the two fences. The total effectiveness of this integrated system is between 25 and 30 years, with the system's unit cost totalling around US$ 198,000 per 1 km, including chain-linked fences, trees and irrigation for one year (Al-Hemoud et al., 2019).

Vegetative techniques may involve either protecting existing vegetation as a preventive measure or planting adapted grasses, shrubs or trees. Careful attention must be paid to the selection of species that are well-adapted to the harsh conditions. Different species may be adapted to various parts of dunes.

Reducing wind speed within and between fields is a critical control measure. Tall vegetation or structures are most effective in reducing wind speed over large areas (**Figure 61**).

Windbreaks can reduce wind speeds by 50–80 per cent in open fields for up to 15–20 times the distance of the height of the windbreak (Burke, 1998; Skidmore, 1986).

The distance of the wind reduction effect is directly proportional to the height of the windbreak. Windbreak porosity also affects the pattern of wind velocity within the shelter zone, with porosity of 20 per cent having been found to maximize the protection distance (Burke, 1998). However, as wind velocity increases and the direction stops moving perpendicular to the barrier, the fully protected zone will start to diminish (Tatarko, 2016).

Nursery operations therefore need careful planning, particularly if the production of large quantities of seedings is anticipated, such as the adoption of drought-resistant species in the dry areas, including for example, *Atriplex* spp. and *Salsola* spp. Careful attention also needs to be paid to the sustainability of water use, especially when planting trees, which may grow well in the first few years but later deplete water tables and die off.

Temporary irrigation is often required to ensure that plants survive during the establishment phase. Efficient methods for irrigation during planting have been established, such as water jetting (UNEP, 2015). Options for planting include seedlings planting, mechanized contour planting (semicircular bunds using the Vallerani system), direct sowing and aerial seeding. Sustainable management and harvesting of vegetation are essential for preventing dune destabilization (FAO, 2010). Only 15 per cent vegetation cover may be sufficient to stabilize sand surfaces (Lancaster, 2011).

Figure 61. Trees used to stabilize sand dunes encroaching on an irrigation scheme on the Nile flood plain

Source: UNEP.

Aerodynamic methods to harness wind to remove sand from urban or other areas have also been used (FAO, 2010). Such methods aim to increase wind speed without introducing turbulence so that deposits are transported away. For example, streets in some Sahelian towns are orientated parallel to the prevailing wind.

Obstacles placed in the path of sand-laden wind can be used to increase wind speed through a compression effect, such as placing stones at a certain distance from one another along the crest of a dune. The removal of obstacles from strips along roads, known as transverse streamlining, has been used to reduce sand accumulation, such as in Mauritania along the Road of Hope, though this needs constant maintenance (FAO, 2010). It is worth noting that protective measures that are not green infrastructures or nature-based need to be considered with a precautionary approach. This approach must take into account all aspects of ecological connectivity in order to avoid unintended negative impacts on other ecological processes such as animal migration.

12.6 Conclusion

Policies for SLM and ILM can best be deployed in the context of the LDN target to address SDS sources. In the LDN target-setting process, there is an opportunity to collectively consider options to mitigate SDS sources, particularly anthropogenic sources, including the assessment and trend of land degradation and identification of land degradation drivers, with the participation of relevant stakeholders linked to land and water resources. An integrated and holistic approach of SLM, land-use planning and ILM can be an integral part of and maximize synergies among various actions to reduce anthropogenic dust emissions at larger scales in the long term.

Regional cooperation is crucial for the management of anthropogenic dust emissions at landscape levels, including water management. Regional mechanisms based on strong political commitment are therefore needed to coordinate policy between source and deposit areas. SDS source management can be integrated into regional processes, where appropriate, and LDN target-setting can be included in policy- and decision-making processes and implemented as a priority in SDS prone areas, with pertinent financial investment and technical assistance provided.

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13. Sand and dust storms impact response and mitigation

Chapter overview

This chapter reviews approaches to address and mitigate the impacts of sand and dust storms (SDS) on humans and the economy. After an overview of SDS preparedness and emergency response procedures, the chapter identifies sector-specific measures to address SDS impacts.

13.1 Introduction

This section of the Compendium looks at ways to mitigate the impact of sand and dust storms (SDS) through preparedness and emergency response procedures (see **chapter 3** for overview of disaster risk management.) To date, most efforts to manage the risks posed by SDS have focused on understanding the mechanisms and origins of SDS (**chapter 2**), monitoring, forecasting and warning of SDS (**chapters 9** and **10**) and mitigation of SDS development at their source (**chapter 12**).

Less attention has been paid, as part of the disaster risk management process, to mitigating the impacts of SDS either as they occur or once they have occurred. This is likely due to the low profile of SDS (see Middleton et al., 2018) and the diverse impacts of SDS across sectors, which together make developing a unified approach complicated. It is expected that, over time, additional examples of responses to SDS will become available and can be integrated into a more comprehensive approach to SDS risk management.

The identification of specific measures for response and impact mitigation should be based on risk and vulnerability assessments (see **chapters 4**, **5** and **7**). The economic effectiveness and cost-to-benefit justification of each of these measures needs to be assessed based on local conditions (see **chapter 6**). In some cases, mitigation measures that are technically possible cannot be justified based on their expected benefits.

Following an overview of SDS preparedness (**chapter 13.2**) and response and SDS disaster planning (**chapter 13.3**), **chapter 13.4** provides an overview of SDS preparedness and response options and specific actions which have been identified to reduce SDS impacts through impact-based warnings, both during and in the immediate aftermath of SDS.

Chapter 13.4 should be read in conjunction with **chapter 12** as there can be considerable overlap between impact and source mitigation in practice.

13.2 Overview of SDS preparedness and response

Preparedness and emergency or disaster response play critical roles in mitigating disaster risk and minimizing impacts. Preparedness for and emergency response to SDS events take place at the individual, family, community and organizational (factory, school, etc.) levels.

As Ejeta et al. (2015) point out, preparedness strategies are developed through identification and mapping of the hazard in question, a vulnerability analysis and a risk assessment (see **chapters 5** and **7** on SDS risk and vulnerability assessments). Knowledge gained in these ways can then be used to develop protective actions.

Effective preparedness reduces vulnerability, increases mitigation levels and enables timely and effective response to a disaster event. These actions will shorten the recovery period from a disaster, while simultaneously increasing community resilience.

Preparedness, apart from building operational capacities and reserves, focuses on educating those at risk to adopt behaviours which reduce risk and increase coping capacities. An interesting example of using education to change behaviour is from the state of Arizona of the United States of America.

Box 22. Sand and dust storms and safe driving guidance

- Avoid driving into or through a dust storm.
- If you encounter a dust storm, immediately check the traffic around your vehicle (front, back and to the side) and begin slowing down.
- Do not wait until poor visibility makes it difficult to safely pull off the roadway – do it as soon as possible. Completely exit the highway if you can.
- Do not stop in a travel lane or in the emergency lane. Look for a safe place to pull completely off the paved portion of the roadway.
- Turn off all vehicle lights, including emergency lights. You do not want other vehicles approaching from behind to use your lights as a guide, possibly crashing into your parked vehicle.
- Set your emergency brake and take your foot off the brake.
- Stay in the vehicle with your seatbelts buckled and wait for the storm to pass.
- Drivers of high-profile vehicles should be especially aware of changing weather conditions and travel at reduced speeds.

Source: Arizona Department of Transport, n.d.

The Arizona state government and National Weather Service website Pull Aside, Stay Alive[1] provides information to drivers on how to respond to the very rapid deterioration in visibility during the sudden onset of dust walls typically associated with a haboob, which is a common cause of dust-related accidents on the Interstate 10 (I-10) highway (see **Box 22**; Day, 1993).

Monitoring, prediction, forecasting and early warning (see **chapters 9** and **10**) facilitate preparedness and emergency response. The development of SDS is monitored using data from satellites, networks of Lidar[2] stations and radiometers, air-quality monitoring and meteorological stations (Akhlaq et al., 2012). All of these sources contribute data to modelling efforts, which enhance our understanding of the processes involved and are used to produce predictions and early warnings (see **chapter 10**).

Operational dust forecasts have been developed at several WMO SDS Warning Advisory and Assessment System (SDS-WAS) centres (see **chapter 9**), as well as by national meteorological and hydrological services (NMHS). However, NMHS capacities to develop and issue SDS warnings vary considerably and warning procedures can vary between countries. Forecasts and warnings can be communicated to the public via a range of media, including television, radio, short message service (SMS) text alerts and smartphone applications, as discussed in **chapter 10**. Intrusive warnings can be provided via messages which break into radio or TV transmissions or send out blanket SMS.

Detailed SDS forecasts are not always needed for warning systems. Forecasting for localized haboobs, which occur at spatial scales of a few kilometres, is under development (Vukovic et al., 2014). However, systems designed to warn drivers of dusty conditions on susceptible highways have been used in the southwest of the United States of America for several decades (Burritt and Hyers, 1981). More recently, remotely-controlled signs are being replaced with systems linked to in situ sensors that detect poor-visibility conditions and alert motorists via overhead electronic signs.

There is evidence to suggest that media alerts of poor air-quality result in behavioural changes that tend to lower exposure to air pollutants (Wen et al., 2009).

1 See www.pullasidestayalive.org.

2 Light detection and ranging.

A similar finding was reached in assessments of the health impacts associated with a severe dust storm in Australia by Tozer and Leys (2013), which highlighted the importance of health alert SMS and emails sent to people advising of a high-pollution event. Further investigation of the Australian event by Merrifield et al. (2013) concluded that because the dust storm and consequent public health messages had widespread media coverage, the health consequences from this particular dust event were likely to represent the optimal health outcomes that could be hoped for in similar future events.

Nonetheless, significant challenges remain with the reception and uptake of SDS warnings. Research indicates that those receiving warning messages can be expected to follow a "milling" process before taking action to respond to a warning, which involves:

- understanding the warning
- believing the warning
- personalizing the warning
- deciding whether to take action based on the warning
- searching and confirming the warning.

The last step can involve visual verification of an SDS approach, which may provide limited time to take protective actions. Furthermore, an individual receiving a warning may not act until they are sure that their family members will be safe (National Academies of Sciences, Engineering, and Medicine, 2018).

While advanced technologies (mobile phones, satellites, etc.) are useful in disseminating warnings, it is not certain that these technologies will always reach all those at risk. In many parts of the world where SDS are common, these technologies are not available or have limited coverage, for example, only major urban centres. As a result, locally managed SDS warning systems are often required.

In many cases, source mitigation measures, as described in **chapter 12**, can be effective in reducing SDS impacts and should be included in preparedness measures.

For instance, increasing vegetation cover in urban landscapes, particularly with trees to slow wind speeds, may reduce the health problems associated with atmospheric PM_{10} and $PM_{2.5}$ concentrations, as well as biological and chemical aspects of pollution (see Janhäll, 2015). In both rural and urban areas, increased vegetation has the potential to reduce pollutants through filtration (see Hwang et al., 2011) and to regulate microclimatic conditions in a way that offers at least perceived benefits and well-being (Lafortezza et al., 2009).

13.3 SDS disaster or emergency planning

Current general good practice is for disaster or emergency plans to be developed at the individual, family, village, town, city, county, province or state and national levels, as well as for industry and business. These plans generally follow a similar model, with individual and family plans focusing on immediate survival after a disaster (for example, stocking food, water, medicine, etc.) and each higher level of plan focusing on providing support to the next lower group, for example, county plans defining support to cities, towns and villages, and state or provincial plans defining support to counties within the state or province.

Hall (2017) identifies four objectives of emergency and disaster planning:

- prevent injuries and fatalities
- reduce damage to buildings and materials
- protect the surrounding community and environment
- facilitate the continuation of normal operations.

Disaster plans can be developed for individuals, communities, public and private facilities, such as airports and hospitals, manufacturing and business units. Given the generally low profile of SDS as a hazard, only a few examples of SDS integration into the different levels of disaster or emergency planning are widely available. An example of guidance on family-level planning is provided in the **Be Prepared, Take Action, Be Informed** video[3] and web page[4] developed by the state of Arizona Department of Emergency and Military Affairs of the United States of America.

An example of state (province) level SDS management planning is contained within the **Oregon Natural Hazards Mitigation Plan 2015** for the state of Oregon of the United States of America (State of Oregon, 2015).

The plan includes an assessment of SDS and historical examples of impacts, references to warnings and impacts, and source mitigation measures.

Box 23. Gender, preparedness and response

The Compendium's special focus section on gender and disaster risk reduction (see **chapter 3**) provides an overview of why including gender is important in addressing SDS and identified gender-related considerations across types of SDS risk management interventions. As a general rule, all public consultations should collect inputs using a gender-based perspective and from vulnerable individuals and groups, carrying out planning based on these perspectives.

In developing preparedness measures, gender, as well as factors defining vulnerability and vulnerable groups, should be incorporated in analysis and actions. Disaster response plans should also incorporate this type of analysis and should define specific impact mitigation measures and approaches which respond to the vulnerabilities identified.

Good practice is to include a gender specialist and disaster risk management in preparedness and response planning and during operations. Staff involved in preparedness or response should be trained on gender and disaster risk management in the normal course of their work.

Photo: Tsubasa Enomoto, UNDP. Drill for emergency evacuation plan

3 https://youtu.be/X3qw5kr51eE.

4 https://ein.az.gov/hazards/dust-storms.

In general, an SDS disaster plan for a specific location or activity (city, school, factory, etc.) should follow the outline of other disaster plans for the same location or activity. Based on current good practice, an SDS disaster plan above the family level could be expected to include the following elements:

- Authorities for the plan (may be included in the overall plan for all disasters).
- An overview of SDS as a hazard in the area covered by the plan.
- A risk assessment (see **chapters 4**, **5** and **7**).
- Specific source and impact mitigation measures based on the risk assessment. This section may include references to subsidiary plans specific to individual sectors, for example, for a hospital or road transport (source mitigation measures would apply if the location is also a source of SDS).
- Warning, information dissemination and public awareness procedures. Warning procedures may include standard operating procedures to effectively disseminate warnings based on the impact-based forecasting approach (World Meteorological Organization [WMO], 2015).
- Operational details or examples of impact mitigation measures, where appropriate (see **chapter 13.4** and **chapter 12**). Providing details or examples can facilitate practising of plans before a disaster and implementation once a warning has been issued.
- Links to other programmes (such as soil conservation), which could play a role in SDS mitigation.
- Sources of information and contacts.

As appropriate, annexes to the plan can include specific procedures for source and impact mitigation and the identification of who takes primary and supporting responsibilities for implementing such procedures. In general, SDS disaster or emergency plans should include sufficient information to allow necessary actions to be taken, ensuring that no excessive details are added that may hinder the use of the plan.

13.4 Sector-specific options to address the impacts of SDS

13.4.1. Overview

The following sections provide summaries of possible impacts of SDS, as well as preparedness and mitigation measures which can be implemented for specific sectors. Source mitigation measures (**chapter 11**) are often also appropriate for impact mitigation, particularly where impacted locations may be also contributing to the overall load of atmospheric sand and dust load.

13.4.2. Agriculture

For sandstorms (for example, blowing sand and moving sand dunes), impact mitigation measures can include:

- installing sand fences near agriculture areas (Al-Hemoud et al., 2019)
- planting trees or shrubs to block the movement of sand and dust (Al-Hemoud et al., 2019)
- deploying equipment and personnel to clear irrigation and drainage channels from sand
- changing harvesting or planting procedures and timing to avoid the impact of moving sand.

In most cases, applying source mitigation measures to reduce the movement of sand before sandstorm conditions develop are more effective than large-scale impact mitigation. However, both may need to be applied in areas where sandstorms are common and threaten large areas.

For dust storms, impact mitigation measures can include:

- wetting crops after SDS to remove dust from plants (dust on plant leaves may affect development)
- closing vents in greenhouses to prevent dust entry
- removing or protecting machinery which may be affected by dust
- reducing the use of farm equipment which could need additional maintenance if used in high-dust conditions (for example, replacement of air filters, cleaning, etc.).

The use of agricultural machinery during SDS also needs to address the impacts of SDS on safe driving and operation, for example, ensuring that workers can be seen by equipment operators.

13.4.3. Construction

For road construction, consideration should be given to:

- safe operation of equipment during limited visibility
- safety of workers around equipment during limited visibility
- stabilization of road terracing and roadbed development so that the winds associated with SDS do not move the material.

Note that assuring good worker visibility is a normal method to improve safety when working near equipment. The nature of SDS may require additional measures to improve worker visibility, including:

- verifying that standard visibility vests work in high-dust environments
- assessing whether goggles and dust masks impact visibility and communication
- ensuring that equipment operators located in cabs have good visibility of work areas (for example, frequent window cleaning may be required).

Photo by REUTERS/Thomas Peter.

These measures are in addition to the health measures that may be needed when working in the hot and dry environments where SDS are common (hydration, protection from solar radiation, etc.).

For building construction, consideration should be given to:

- erecting physical cloth or plastic sheet curtains to limit dust entry into working areas (but with adequate air conditioning when needed)
- using water sprays or misters to reduce dust load in work areas
- assessing and addressing any limitations in worker visibility or ability to be seen or heard when using goggles and dust masks
- initiating the operation of air-conditioning systems early in a building's construction, along with permanent or temporary (for example, plastic sheeting) closure of openings to the outside of buildings or within them to reduce dust entry and remove dust from work areas (these measures need to take into account fire safety).

These measures can also improve overall working conditions within buildings.

In addition, for both road and building construction, source mitigation measures should be in place to limit the generation of dust during normal times and SDS events.

13.4.4. Education

In education facilities:

- procedures can be initiated before SDS events to reduce dust entry, by closing and sealing windows
- dust rooms[5] can be constructed onto entry ways
- misters can be used to reduce dust load at entry ways and within large open areas
- air-conditioning systems can be operated in a way to increase filtering (though filters would need to be cleaned or replaced more frequently)
- in-room air filter units can be used as needed to reduce dust loads
- schedules for collecting and returning students using buses or other means of transport can be modified to limit their exposure to SDS outside the education facility
- special procedures should be developed to assist students and staff with health conditions that can be affected during SDS (such as asthma, impaired vision, etc.).

For education institutions with dormitories, implementing an SDS response will need to include the participation of dormitory residents. Models for engaging students in SDS response addressing transport-related issues can be taken from procedures for dealing with severe weather, such as thunderstorms and tornadoes.

These measures can be integrated into school emergency plans and, with the exception of dust rooms, be put in place when an SDS warning is received.

Knowledge about SDS, their causes and impacts, can be integrated into school curriculum. Most curriculum include natural science and increasingly include core or supplemental topics on natural hazards and disaster management into which SDS management can be integrated.

In addition, education on SDS can be undertaken by interest groups in schools, such as an environment club, community organizations, including scouts and girls' or boys' clubs or other such organizations.

Note that these measures apply to all levels of the education system, from preschool to university. Facilities at each level in the education system should have disaster management plans, with this being a legal requirement in many countries.

5 A dust room would serve as an area where outside air would be physically isolated from inside air to limit dust from entry though doorways.


Photo: UNDP Indonesia

These plans should include SDS early warning and impact mitigation.

13.4.5. Electricity

Interventions to address the impact of SDS on electricity generation, transmission and use are most likely in the following areas:

- Generation – Clean solar panels of dust and protect equipment from short- and long-term impacts of dust by improving the filtration of air taken in directly by equipment, (for example, diesel generators), and in the environment where the equipment operates (for example, generator rooms), based on forecasts[6] and warnings.
- Transmission – Ensure that winds associated with SDS do not damage transmission lines or equipment, including measures taken before any severe weather to limit damage.
- Demand – Anticipate, based on previous SDS events, increases in electricity demand from cleaning activities after the event and during the event from increased use of air conditioners and other equipment.

13.4.6. Health

The two immediate threats to the health sector come from:

- the movement of dust into health facilities, which impacts hygiene in the facility, the operation of equipment and testing, and the health of patients
- an increase in the caseload of individuals with health conditions that are aggravated by sand or dust conditions.

6 Electricity generation planning can use weather forecasts to anticipate SDS and identify impacts several hours to several days in advance, incorporating this into operational plans.

Measures to reduce the impact of sand and dust on a health facility include:

- sealing windows and other openings before SDS to reduce air entry from outside
- using dust rooms at entry ways to physically isolate dust from inside air and limit it from entering though doorways
- using misters to reduce dust load at entry ways and within large open areas
- using air-conditioning systems to increase air filtering (filters would need to be cleaned or replaced more frequently)
- using in-room air filter units to reduce dust loads
- frequent use of wet mopping to remove dust from floors and other surfaces
- washing clothes exposed to sand and dust to reduce secondary entrapment, specifically inside areas that have been isolated from SDS events (such as rooms with sealed windows)
- modifying opening and closing schedules to limit exposure to SDS
- reducing movement into spaces where sensitive equipment is located or tests take place
- increasing the use of breathing apparatus designed to reduce air intake from ambient air, for example, using a face mask instead of a cannula.

Measures to reduce the impact of increased caseloads associated with an SDS event include:

- increasing staff based on an SDS warning
- increasing supplies of treatment drugs and equipment
- separating triage and treatment facilities from the main health facility, incorporating the aforementioned methods, such as dust rooms, misters and air conditioning
- increasing potential patients' knowledge of ways to reduce or avoid the impacts of SDS, which can involve long-term education for SDS-vulnerable patients, as well as messaging as part of SDS warnings on how to reduce SDS impacts.

13.4.7. Hygiene

Living facilities (houses, apartments, care facilities, public offices and commercial markets and places of assembly) can take actions similar to those for education facilities:

- sealing windows and other openings before SDS to reduce air entry from outside
- using dust rooms at entry ways to physically isolate dust from inside air and limit it from entering though doorways
- using misters to reduce dust load at entry ways and within large open areas
- using air-conditioning systems to increase air filtering (filters would need to be cleaned or replaced more frequently)
- using in-room air filter units to reduce dust loads
- wet mopping frequently to remove dust from floors and other surfaces
- washing clothes exposed to sand and dust to reduce secondary entrapment, specifically inside areas that have been isolated from SDS events (such as rooms with sealed windows)
- modifying opening and closing schedules to limit exposure to SDS.

For some public facilities, including shopping malls and closed markets, expanding hygiene efforts can be part of activities to provide safer places as refuge from SDS for those who may be outside when the event developed (such as a haboob). This activity would be similar to the establishment of warming spaces, such as tents, during extreme cold events, or to cooling spaces during extreme heat events. In some situations, cooling spaces will be needed at the same time as SDS events.

13.4.8. Livestock

SDS impacts on livestock, including cattle and other ruminants, horses, goats, sheep, ducks, geese and other animals kept in controlled situations (for example, not ranging without human intervention) include:

1. respiratory problems
2. difficulty accessing food if pastureland is covered in dust or sand
3. entering into traffic or water sources in an effort to avoid the dust or sand, or because of poor visibility.

Livestock owners or managers should develop a plan for managing SDS based on local conditions and also seek expert advice from specialists and veterinarians on animal health impacts and normal reactions to SDS by the animals of concern. Specific measures that can be considered to reduce impacts include:

- moving animals to enclosed areas before SDS events
- moving animals inside before SDS, but considering the need for adequate ventilation, water and food for the duration of the event
- providing additional food stocks if normal food supplies (for example, pasture) is covered by sand or dust
- allowing animals to move to open rangelands to reduce excitement that may be due to SDS, such as haboobs, and associated with thunder or heavy winds and rains (though care should be taken to ensure that moving animals does not put them at risk of lightning strikes)
- moving animals away from roads and waterways to avoid unplanned movements into these areas.

If animals are being kept inside a building, it is important to consider the environmental conditions (heat and humidity) within the building if a large number of animals are present and normal ventilation has been shut down because of the SDS. This could lead to hot and humid conditions which contribute to animal health issues.

If SDS are common, developing an understanding of common local practice is important as these animals may have adapted to this hazard from experience. Measures such as misters may be tested to reduce temperatures and dust loading. Masks are unlikely to be effective.

13.4.9. Manufacturing

Impact mitigation for manufacturing is likely to fall into three areas:

- reducing the entry of dust into facilities through closing and sealing windows and other openings, improving filtering and using air locks and positive pressure to block inward air movement
- reducing the dust load carried by employees and others entering facilities by requiring a change of clothes or the use of overalls
- increasing the cleaning of raw materials, parts supplied and items manufactured to reduce the presence of dust.

Although these measures are likely to be common practice during non-SDS periods, they can be expanded and upgraded through, for example, additional washing or resealing of openings, based on SDS forecasts and warnings.

13.4.10. Public awareness

Improving public awareness of SDS impacts can improve the uptake of warning messages (see **chapter 9**) and the overall adoption of impact mitigation measures. Awareness can be raised through:

- the education system (see **chapter 13.4.4**)
- information campaigns before and during expected SDS periods
- site-specific SDS information, usually integrated into early warning messages (see **chapter 10**).

Raising public awareness about hazards, potential disasters and impact mitigation is a major task of national and subnational disaster management offices, with considerable experience and documentation on these types of efforts available. See the document **Public Awareness and Public Education for Disaster Risk Reduction: Key Messages** (International Federation of Red Cross and Red Crescent Societies [IFRC], 2013) for a starting point on public awareness and impact mitigation.

13.4.11. Sport and leisure

In most cases, outdoor sports and leisure activities would be cancelled based on SDS forecasts and warnings. Due to the short lead time and short duration for haboobs, it can be useful to set up temporary refuges (for example, in a sports hall) so that people can avoid driving during the immediate passage of a storm (see **chapter 13.4**.**12** on transport).

In any case, the organizers of outdoor sports and leisure events during periods of possible SDS should:

- be in contact with weather and disaster management services to get timely forecast and warning information
- have plans on managing SDS events, coordinated with local authorities as needed
- have assessed and be prepared for the immediate health impacts of SDS on health-compromised individuals, including training immediate responders, stockpiling emergency supplies, planning evacuations to health facilities with local health authorities and providing warnings specifically for these individuals when SDS are expected.

Indoor events are less likely to be directly affected by SDS. However, plans should be developed to:

- seal windows and other openings before SDS to reduce air entry from outside
- open dust rooms at entry ways to physically isolate dust from inside air and to limit it from entering though doorways
- use misters to reduce dust load at entry ways and within large open areas
- use air-conditioning systems to increase air filtering (filters would need to be cleaned or replaced more frequently)
- use in-room air filter units to reduce dust loads
- wet mop frequently to remove dust from floors and other surfaces
- modify opening and closing schedules to limit exposure to SDS
- identify how to adjust participants' road transport plans to limit driving in severe dust conditions, including driving at night when dust can have the same impact as fog on visibility.

13.4.12. Transport

The transport sector has received considerable attention with respect to reducing the impact of SDS. For air transport, civil aviation regulations, company operation procedures, advances in technology and improved SDS forecasting and modelling have been generally effective in reducing the risk posed by SDS in their various forms (see Baddock et al., 2013, for an example from Australia).

The greatest risk to air transport likely comes from aircraft flying into unanticipated SDS conditions (such as haboobs or the Harmattan front) and attempting to land with limited visibility. This seems less likely to occur with scheduled air services, which are supported by dedicated weather services, and more likely with private or small commercial operations, based on experiences in the Sahel.

Specific measures to reduce the impact of SDS on aircraft (and their users) include:

- using forecasts to identify whether SDS are possible at the destination or on-route
- deciding not to fly to a destination where SDS may occur during the flight or close to the expected landing
- landing in advance of forecasted SDS or at an alternative airport where SDS conditions are severe at the intended destination
- plugging or covering vents, intakes and tubes to prevent dust from entering and sealing windows and doors, if possible
- ensuring that all intakes are clear of dust, plugs and covers before starting the aircraft
- vacuuming the inside of the aircraft after SDS to improve hygiene, limit secondary dust entrapment, reduce the need to replace air filters and reduce impacts on sensors and instruments (adapted from SKYbrary, 2019).

Conditions similar to those found in SDS can also develop for helicopters in the final stages of landing or on taking off from unimproved landing sites (for example, no pavement). These "brown-out" events are the result of the helicopter blades causing dust, sand and other small items to become airborne when the aircraft is very close to the ground. These events can cause pilot disorientation and difficulty in landing (Rash, 2006).

Ways to address this problem include:

- pilots being ready to use instrument landing procedures when brown-out is expected
- covering the landing area with a chemical treatment to prevent dust, sand and debris
- watering the area where an aircraft will land to remove conditions that allow dust and sand to be entrained in the downdraft from the aircraft (adapted from Rash, 2006).

Overall, the challenge in reducing the impact of SDS on road transport is significant. The greatest risk to this transport likely comes from haboobs or locally-blowing dust associated with agriculture (for example, ploughing fields).

Impact mitigation for road transport includes the following:

- risk assessments and the identification of specific SDS source areas and times of year (this applies to both haboobs and dust from agricultural activities, which can be time- and location-specific)
- public awareness (see **chapter 13.4.10**), including posting signs in possible SDS locations
- planning, including annual awareness campaigns, site mitigation measures (such as sand fences) and response to forecasts and warnings
- information collection, research and source mitigation plans to reduce long-term risk and improve the understanding of local conditions that can generate SDS
- site-specific warning messages, safety patrols and traffic controls (for example, warning lights or changes to speed limits when SDS are forecast).

An example of these steps comes from Arizona in the United States of America, where the National Weather Service and state and local authorities have developed a programme to collect research on SDS, disseminate the information to at-risk populations, use the information in impact and source mitigation and develop public awareness on how to manage SDS while driving. Information on the Arizona effort can be found at:

- Arizona Emergency Information Network, Dust Storms: https://ein.az.gov/hazards/dust-storms
- National Weather Service, Dust Storm Workshops: https://www.weather.gov/psr/DustWorkshops
- City of Phoenix, Storms and Monsoons: https://www.phoenix.gov/emergencysite/Pages/Storms-and-Monsoons.aspx

- Monsoon Safety, Thunderstorms and Dust Storms: http://www.monsoonsafety.org/facts/dust-storms.htm.

The Arizona programme also includes a public information video titled *Pull Aside, Stay Alive*.[7]

In addition, the Arizona State Department of Emergency and Military Affairs has developed an SDS video on the theme of preparedness, taking action and being informed, which includes specific guidance on what to do when driving near or into SDS, as well as other impact mitigation advice.[8]

13.4.13. Water and sanitation

SDS impacts on water quality are expected to primarily result in an increased sediment load as dust settles on water supplies. The impact is expected to be larger the greater the surface area of water covered by dust.

Reducing the impact of dust will require water filtration both at the water supply systems level and the individual (household) level for water storage containers. The need to filter SDS-contaminated water may reduce the throughput of large-scale treatment operations and increase the quantity and cost of deflocculating (pre-filtering removal of impurities) from the water. Filtering SDS-contaminated water at the household level may not be needed (for example, if the level of contamination is small) or can be done using normal water filters.

Efforts to remove dust from water supplies may be justified based on chemical or biological contaminants transported on or with dust. This risk should be assessed before SDS events.

If needed, measures for cleaning large and small water supplies can be developed, with public education on the need to clean household water supplies incorporated into the SDS public awareness process.

Some of the sanitation-related impacts of SDS are likely to be addressed through the measures described under the chapter on hygiene (**chapter 13.4.7**). However, based on actual SDS impacts and time and resources available, SDS-related sanitation measures will likely focus on:

- washing streets, sidewalks and public areas to remove dust
- clearing accumulated sand from drains and drainage systems (in urban areas)
- increasing sewage treatment plant operations to deal with additional greywater produced from hygiene-related activities (such as increased washing of clothes, floor cleaning, etc.).

13.5 Conclusions

There are a range of measures that can be taken to prepare for and mitigate the impacts of SDS. The selection of specific measures needs to consider the type of SDS that may occur, the extent to which a warning is possible, and the nature of the activities being undertaken when SDS may occur. Where not yet already in existence, SDS preparedness and response plans ranging from the individual to national levels should be developed as a normal part of disaster risk management, based on standard approaches to disaster planning. In all cases, education about SDS and impact mitigation measures should be provided to anyone at risk, even if for a short time, and should be supported by warning and preparedness plans.

7 Available at http://www.pullasidestayalive.org/.

8 The video is available at https://youtu.be/X3qw5kr51eE and is presented in sign language as well as spoken word with images.

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Platz der Vereinten Nationen 1,
D-53113 Bonn, Germany
Tel: +49 (0) 228 815 2873

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