Global Assessment of Sand and Dust Storms

UNEP WMO UNCCD

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Foreword

Large sand and dust storms, which result from a combination of strong winds and loose dry soil surfaces in arid and semi-arid areas, are detrimental to human health, agricultural land, infrastructure, and transport. Every year, an estimated 2,000 million tons of dust is emitted into the atmosphere. While much of this is a natural part of the biogeochemical cycles of the Earth, a significant amount is generated by human-induced factors, especially unsustainable land and water management.

However, there is considerable uncertainty about whether sand and dust storms are increasing in intensity and frequency and how much is due to human causes. There is also need for greater clarity on the role that climate change is playing and how changes in dust emissions due to land use and climate change may impact the atmosphere, climate and oceans in the future. Policymakers and other stakeholders need more information on what can be done to reduce the frequency and intensity of sand and dust storms and to protect infrastructure and human health from their effects.

The Global Assessment is a significant contribution to our understanding, synthesizing the latest scientific information on the causes of sand and dust storms and their consequences for human and environmental well-being. It summarizes the latest knowledge on predicting them and reducing their impact.

Given the dominance of natural sources of dust and uncertainty regarding future dust emissions, the report stresses the importance of protective measures, which include enhancing monitoring, prediction and early warning systems, and improving preparedness and emergency response. To reduce anthropogenic sources of sand and dust storms, the Assessment recommends integrated strategies that promote sustainable land and water management in cropland, rangelands, deserts and urban areas, and climate change mitigation.

The report proposes a consolidated and coordinated global policy for responding to sand and dust storms, integrated and synergistic actions across sectors, and strengthened cooperation among global institutions. These measures are integral to the success of the 2030 Agenda for Sustainable Development. They can contribute to improved public health, more liveable towns and cities and more sustainable rural areas. They can help combat climate change, conserve oceans, and protect terrestrial ecosystems, thereby helping to reduce poverty and protect economic growth.

I commend this report to all Governments and stakeholders engaged in reducing the occurrence and impact of sand and dust storms and working to achieve the Sustainable Development Goals.

Ki Moon Ban

BAN Ki-moon
United Nations Secretary-General

Executive summary

Background

Sand and dust storms (SDS) occur when unchecked, strong or turbulent winds combine with exposed loose soil dry surfaces. These conditions are common in semi-arid and arid regions. Sand storms occur relatively close to the ground surface, but finer dust particles may be lifted kilometres high into the atmosphere, where strong winds transport them long distances, even across continents. SDS have become of increasing concern among governments and the international community because of their damaging effects on human health, agricultural land, infrastructure, and transport. Key questions that are important to answer for policy decision making include: (i) have dust storms got worse in recent decades; (ii) to what degree are SDS a result of human activity, and (iii) what can be done to prevent them and protect ourselves from their impact? This global assessment of SDS has been prepared by UNEP in partnership with WMO and UNCCD, in response to calls for action on SDS. The assessment aims to synthesise the latest knowledge on the science and policy of SDS and apply this knowledge to identify elements of a comprehensive strategy for SDS mitigation at the local, regional and global levels. The report is intended to increase awareness among decision-makers and stakeholders about the opportunities for managing SDS and for encouraging partnership towards combined actions for reducing negative environmental and development impacts of SDS.

Drivers

Although there are large uncertainties on the precise numbers, most (about 75%) of current global dust emissions come from natural, not anthropogenic sources. These are topographic depressions in arid regions, mainly dry ancient lake beds with little vegetation cover. Anthropogenic sources, which make up about 25% of global dust emissions, are mainly (85%) from hydrologic sources (ephemeral water bodies). The dominance of natural sources, coupled with a growing risk of increased anthropogenic contributions, has important implications for SDS mitigation strategies.

The activity of a sand or dust source depends on the fraction of surface winds exceeding the erosion threshold defined by the local surface properties. Most major dust sources are dominated by inland drainage basins in arid areas, due to the wind-erodible nature of their surface materials, exacerbated by the dry conditions, and the limited vegetation due to aridity. Removal of vegetation, loss of biodiversity, and disturbance of the sediment or soil surface (e.g., through destruction of biological crusts by vehicles), will increase susceptibility to dust generation in these areas.

Human-induced hydrological changes, often driven by demand for water in areas adjacent to natural sources, has led to desiccation of wet or ephemeral water bodies and increased SDS risk. Unsustainable land use and land degradation, especially in semi-arid areas, poses an important risk for increased wind erosion, which can have damaging effects on agricultural productivity even without producing SDS. Vegetation provides a protection mechanism, by acting as a mechanical barrier, controlling wind flow and reducing surface shear stress at the ground surface, by physical protection of the soil surface, and by increasing soil stability through recycling organic matter. Any factors that lead to unsustainable land use and reduction of vegetation cover in susceptible areas increase SDS risk. Major dust bowl events in various parts of the world have occurred due to a combination of prolonged drought and unsustainable land management practices.

Climate change is an important potential driver of future wind erosion and SDS risk, especially the occurrence of more extreme wind events and movement to drier climates, but reverse effects are also possible. There are multiple feedbacks between anthropogenic dust emissions, climate and both terrestrial and ocean biogeochemical cycles, which make it difficult to predict the impact of climate change and increased anthropogenic dust emissions on the balance of the Earth system. Land degradation also contributes to climate change through production of greenhouse gases, changes in surface energy balances and direct contributions of dust to the atmosphere. Simulations suggest a high sensitivity of dust emissions to human intervention, which has large implications for climate and biogeochemistry in the future, and precautionary principles should be applied.

State and trends

SDS are characterized and tracked using a combination of satellite imagery, ground monitoring observations and numerical modelling. The largest areas with high dust intensities, which derive from both natural and anthropogenic sources, are located in the Northern Hemisphere, mainly in a broad "dust belt" that extends from the west coast of North Africa, over the Middle East, Central and South Asia, to China. The Southern Hemisphere is devoid of major dust activity, with small concentrations in central Australia, in southern Africa, the Atacama in South America, and the North America Great Basin, although these sources have large local impacts.

The report provides detailed description of dust sources, trends and trajectories for different regions. The Sahara is the most significant dust source globally and is mostly natural, whereas the southern Sahel sources are overwhelmingly anthropogenic, thought to be mainly due to agricultural and grazing activities. Sources in the Atlas Mountains and along the Mediterranean coast are also mostly anthropogenic. The Middle East shows a complex mixture of natural and anthropogenic sources with Mesopotamia being a major source area. Southern Africa possess two of the three largest dust sources in the southern hemisphere, namely the Etosha and Makagadikgadi basins. The greatest dust activity in North America occurs in the high plains, extending from Montana to southern Texas, and is primarily anthropogenic except for a few ephemeral lakes. In South America the largest natural sources are the Atacama Desert of Chile and Peru, whereas the main anthropogenic sources are in the Argentine Pantagonia. The northern part of the Indian sub-continent is a major dust source, largely associated with ephemeral water bodies ranging in scale from the major rivers to small lakes, driven by land use. There is a high frequency of dust storms at the convergence of the borders of Iran, Pakistan, and Afghanistan. In East Asia the largest natural sources are associated with basins in China and include the Taklamakan Desert.

Simulations suggest that global annual dust emissions have increased by 25% to 50% over the last century due to a combination of land use and climate changes. SDS frequency and severity have increased in recent decades in some areas but decreased in other areas. There appear to have been no major changes in dust activity over the past three decades over North Africa, the Middle East and South America, whereas there have been substantial changes in the US high plains, central Asia and Australia. There is evidence to support positive impacts of improved land management on reducing SDS in some regions.

Climate change projections suggest that regions that are currently dusty areas and which are likely to become drier include most of the Mediterranean areas of Europe and Africa, northern Sahara, central and west Asia, southwest USA, and southern Australia. Precipitation has increased in mid-latitude land areas in the Northern Hemisphere since 1950, which might help to reverse desertification in the mid-latitude belt. Dusty regions that are likely to become wetter include eastern Africa and east Asia, whereas large model uncertainties preclude projections for the Sahel-Sudan, the Gangetic basin and the Lake Eyre region.

Impacts

Dust deposition has both positive and negative environmental impacts. Dust affects the climate system, possibly changing the earth’s radiative balance and modifying tropical cyclones, which can cause drought intensification. On the other hand, dust can enhance precipitation by acting as droplet nuclei. Dust provides nutrients to terrestrial ecosystems and ocean surface waters and the seabed, boosting primary productivity, especially through relieving phosphorus limitation to nitrogen fixation, and through iron fixation, which boosts phytoplankton growth. Primary productivity in turn affects the global carbon cycle. Saharan dust fertilizers the Amazon rainforest, providing a phosphorus input comparable to the hydrological loss from the basin. Similarly, Hawaiian rain forests receive nutrient inputs from dust from central Asia. On the other hand, dust from Africa and Asia may have harmful effects on coral reefs in the Americas.

Dust causes numerous human health problems globally, but especially in arid and semi-arid regions. Inhalation of fine particles can cause or aggravate diseases such as asthma, bronchitis, emphysema (damage of the air sacs in lungs), and silicosis (lung fibrosis). Chronic exposure to fine dust is associated with premature death due to cardio-vascular and respiratory disease, lung cancer, and acute lower respiratory infections. Fine dust carries a range of pollutants, spores, bacteria, fungi, and potential allergens. Other common problems include eye infections, skin irritations, meningococcal meningitis, Valley fever, diseases associated with toxic algal blooms, and mortality and injuries related to transport accidents. In Sahelian countries there is a strong correlation between dust loads from the Sahara and meningitis outbreaks.

SDS have wide ranging economic impacts, both immediate and long-term. In addition to the environmental and health impacts above, short-term costs include crop damage, livestock mortality, infrastructural damage (e.g., buildings, power, communications), interruption of transport and communications, air and road traffic accidents, and costs of clearing sand and dust. Longer-term costs include chronic health problems, soil erosion and reduced soil quality, soil pollution through deposition of pollutants, and disruption of global climate regulation. Economic losses from a single SDS event can be in the order of hundreds of million dollars. However, the benefits of dust are rarely quantified.

Existing policy actions

The report provides an overview of major existing global, regional and related national policy actions relevant to SDS management. The WMO has established the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) with the mission to enhance the ability of countries to deliver timely and quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities. SDS-WAS has established regional nodes for Northern Africa, Middle East and Europe; Asia and Central Pacific; and Pan-America. All centres preform observation, forecasting and capacity building. Other initiatives include the Barcelona Dust Forecast Centre, the European Union's earth observation programme (Copernicus), and the International Cooperative for Aerosol Prediction. There is a vision to extend these initiatives into a global Dust-Health Early Warning System (D-HEWS).

Actions required to tackle the drivers of SDS are consistent with actions recommended to tackle land degradation, terrestrial biodiversity, and climate change mitigation under the three respective Rio conventions. Northeast Asia and West Asia have developed Regional Action Plans on SDS and the Northeast Asia plan is in full operation. Under UNCCD Regional Action Plans and their associated national plans, there are initiatives to establish green walls on desert margins in both China and Africa. China has well developed desertification action and monitoring programmes. There are a number of regional air pollution agreements and policies that have potential to address SDS.

Policy framework

The report's findings are synthesised into a framework for action, which outlines essential measures for SDS mitigation. In the short to medium-term, there is need to reinforce protective strategies to reduce negative impacts of SDS on human health, infrastructure and operations. Global synthesis and exchange of existing knowledge and best practices for green technology and their associated economic opportunities could generate faster uptake and value.

Given the dominance of natural sources of dust and the uncertainty in future dust emissions, monitoring, prediction, and early warning will be critical for mobilizing emergency responses, as well as for prioritising long-term sustainable land management measures. The report contains an extended section describing existing efforts. Further efforts are recommended towards creating a Global Dust-Health Early Warning System, building on the SDS-WAS initiative.

Investment in the linkages between early warning information and required emergency responses is an area in need of greater attention. Preparedness and emergency response procedures need to cover diverse sectors, such as public health surveillance, hospital services, air and ground transportation services, and public awareness. There is need for a global initiative to develop best practice guidelines and build national capacity in SDS preparedness and emergency responses across different sectors, drawing on the experience from different regions and countries.

In the longer term, the emphasis should be on integrated strategies that promote sustainable land and water management in landscapes, including cropland, rangelands, deserts, and urban areas.

In natural areas, especially deserts, measures should aim to avoid human disturbance of active and potential source areas, and avoid hydrological changes due to human activity in adjacent areas. In human-dominated ecosystems, recommended technical measures to reduce wind erosion and SDS include strategies to maintain soil cover and reduce soil disturbance through various improved cropping practices, including reduced tillage and conservation agriculture, improved rangeland management, and reducing wind speed through use of wind-breaks and agroforestry. The review also covers control measures for industrial settings and protection of urban areas and infrastructure from sand movement, for example through sand dune stabilization.

Large uncertainties remain on the role of dust in the Earth system and the feedbacks between land, oceans, atmosphere and climate, as well as interaction with climate change. A global initiative to provide research coordination, decision-focused priority setting and support, and research synthesis on SDS is proposed.

The report proposes a consolidated and coordinated global policy directly responding to SDS, to help create awareness of the potential for integrated and synergistic actions across sectors and foster strengthened cooperation among relevant institutions at a global level. To help further develop and implement this global policy framework, consideration may be given to the creation of a global SDS virtual centre involving SDS-WAS and other UN Agencies, and interested countries and organisations, which may include: (i) a global scientific initiative, (ii) a platform for early warning and resilience, and (ii) a global platform for policy dialogue and coordination.

1. Introduction

1.1 Sand and dust storm significance

Sand and dust storms (SDS) are lower atmosphere events that result from wind erosion liberating sediment participles from the ground surface. Sand storms occur relatively close to the ground surface, but finer dust particles may be lifted kilometres high into the atmosphere, where strong winds transport them long distances. As bare ground is most susceptible to sediment entrainment, these events usually occur in semi-arid and arid areas where vegetation cover is limited.

Dust storms may travel thousands of kilometres from source areas, passing over land and ocean, and depositing materials far from their source areas. Dust storm trajectories are part of natural ecological systems in arid and semi-arid regions and rates of aeolian deposition may be of similar magnitude to rates of fluvial and aeolian erosion (Goudie and Middleton 2006).

SDS have a number of effects on the environment, both positive and negative: the various interactions are complex and not yet fully understood (Knippertz *et al.* 2014). Dust affects atmospheric, oceanic, biological, terrestrial and human processes and systems (Washington and Wiggs 2011). For example, dust plays a major role in the earth's biogeochemical cycles, fertilizing and sustaining both oceans and forests (Goudie 2009). Dust affects the climate system, modifying tropical storm and cyclone intensities (Evan *et al.* 2006) and changing the earth's radiative balance, which can cause drought intensification (Han *et al.* 2008; Highwood and Ryder 2014). On the other hand, dust can enhance precipitation by acting as droplet nuclei (Nenes *et al.* 2014).

Airborne dust causes or aggravates human health problems (WHO 2013). Chronic exposure to fine particulates is associated with premature death due to cardio-vascular and respiratory disease, lung cancer, and acute lower respiratory infections. Inhalation of fine dust particles exposes individuals not only to hazardous fine mineral particulates, but also to harmful combinations of pollutants, spores, bacteria, fungi, and potential allergens carried along with mineral dusts (Kellogg *et al.* 2004; Smith *et al.* 2011). Poor visibility, sand movement and deposition as a result of SDS also increase incidences of road accidents and aviation hazards.

Beyond impacts on human health, there are multiple economic impacts of SDS. These include disruption of communications, transportation and supply chain infrastructures (Goudie and Middleton 2006). SDS can result in removal of fertile top soils, directly damage crops, and kill livestock, increasing costs of food production and threatening sustainability of production (Middleton and Sternberg 2013; Sivakumar 2005).

SDS have a wide geographical extent, as they occur in all world regions and are trans-boundary in nature (Figure 1.1). Their impacts on achieving sustainable development are therefore significant at the local, regional and global levels and call for joint efforts at all of these scales.

Key questions that are important to answer for policy decision making include:

- Have dust storms got worse (more frequent and severe) in recent decades?
- To what degree are SDS a result of human activity?
- What can be done to prevent them and protect ourselves from their impact?

This assessment aims to shed light on these questions by synthesizing the latest scientific evidence. However, right from the outset, it is important to clarify that most (75%) of current emissions come from natural, not anthropogenic sources (Goudie and Middleton 2006; Ginoux *et al.* 2012). In fact the largest dust sources in the world are topographic depressions in arid regions far from populated areas (Muhs *et al.* 2014). In addition, dust storm activity in the past has been substantially greater than at present (Thomas 2011) and there is substantial uncertainty over the amount of dust emission that is due to human activity. It is also important to note that there is no consistent global trend of increasing SDS frequency and intensity in recent decades: SDS appear to have increased in some areas and decreased in others (Goudie and Middleton 2006). It is important to uncover the causes of these differences and to untangle the effects of human actions from natural causes, including climate change, to guide better strategies for mitigation of SDS.

The exponential increase in scientific publications on SDS since the 1950s, reflects increasing global concern over the problem and increasing awareness of the importance of dust in Earth processes (Figure 1.2). In particular, there has been increasing recognition of need to include dust in climate change models (Washington and Wiggs 2011).

1.2 Policy context

In 2007, the 14th World Meteorological Congress highlighted the importance of the SDS problem and endorsed launching of the implementation of a Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) (WMO 2015). SDS-WAS was established in response to the intention of 40 WMO member countries to improve capabilities for more reliable sand and dust storm forecasts. Forecasting products from atmospheric dust models may substantially contribute to risk reduction, resulting in societal benefit. To be effective, forecasting needs to rely on real-time delivery of products.

More than 15 organizations currently provide daily dust forecasts in different geographic regions. The SDS-WAS, which is a federation of partners organized around regional nodes, integrates research and user communities (e.g., health, aeronautical, and agricultural users). Presently there are three nodes: the Northern Africa-Middle East-Europe Node (hosted by Spain), the Asian Node (hosted by China) and the Pan America node (hosted by Barbados and the USA). The SDS-WAS mission is to achieve comprehensive, coordinated and sustained observations and modelling capabilities in order to improve the monitoring of sand and dust storms, to increase the understanding of dust processes, and to enhance dust prediction capabilities. Further to these efforts, UNEP, WMO and the UNCCD have assisted in the development of regional SDS action plans for both West Asia and Northeast Asia. Members of the 17th World Meteorological Congress (2015) also recognized that sand and dust storms "have considerable impacts on, especially those in, around and downwind from arid and semi-arid regions".

The importance of the SDS problem was recognized by the G77 and China Ministerial Declaration on 26 September 2013 (A/68/595) in which "The Ministers stressed the need to cooperate at the global and regional levels with a view to preventing and managing dust storms and sandstorms, including in the sharing of related information, forecasting and early warning. The Ministers stressed that combating such storms demands financial support and the transfer of technology from developed countries to developing countries".

In addition, at the seventieth session the United Nations General Assembly (UNGA), a draft resolution on combating sand and dust storms was introduced by the Second Committee (Res No. A/RES/70/195). The resolution acknowledges that dust and sand storms pose a severe impediment to the sustainable development of affected developing countries and the well-being of their peoples, and recognizes the fact that dust and sand storms in the last few years have inflicted substantial socioeconomic damage on the inhabitants of the world's arid, semi-arid and dry sub-humid areas, especially in Africa and Asia.

The UNGA resolution emphasizes the need to strengthen the leadership role of the United Nations system, supported by related regional, subregional and interregional organizations, in promoting international cooperation to mitigate and contain this phenomenon in the affected developing countries, including through (i) capacity-building measures, (ii) the implementation of regional and subregional projects, (iii) the sharing of information, best practices and experiences, (iv) the boosting of technical cooperation, (v) the mobilization of necessary financial resources and the setting up of institutions, such as expert committee working groups, and (vi) preparation of master plans and formulation of action plans and programmes to facilitate and enhance such cooperation. The resolution also requested the Secretary-General to present a report to the General Assembly at its seventy-first session containing information and analysis of trends in the occurrence of dust storms.

The UNGA SDS resolution was re-enforced at the second session of the United Nations Environment Assembly (UNEA-2), held in May 2016, with the adoption of a further resolution on sand and dust storms (Res. No. 2/21), which calls on United Nations entities to promote a coordinated approach to combatting sand and dust storms globally; and invites member States, regional development banks and others in a position to do so to contribute financial resources towards regional initiatives and projects to address the challenge of sand and dust storms.

1.3 Aims and scope of the assessment

This global assessment of sand and dust storms has been prepared by UNEP in partnership with WMO and UNCCD, in response to the above calls for action on SDS. The assessment aims to synthesise the latest knowledge on the science and policy of SDS and apply this knowledge to identify elements of a comprehensive framework for mitigating SDS at the local, regional and global levels. The assessment is intended to increase awareness among decision-makers and stakeholders about the opportunities for mitigating SDS and for encouraging partnership towards combined actions for reducing negative environmental and development impacts of SDS. In this report, we define SDS mitigation to mean actions to reduce anthropogenic causes of SDS and to lessen the negative impacts of SDS on human well-being and the environment.

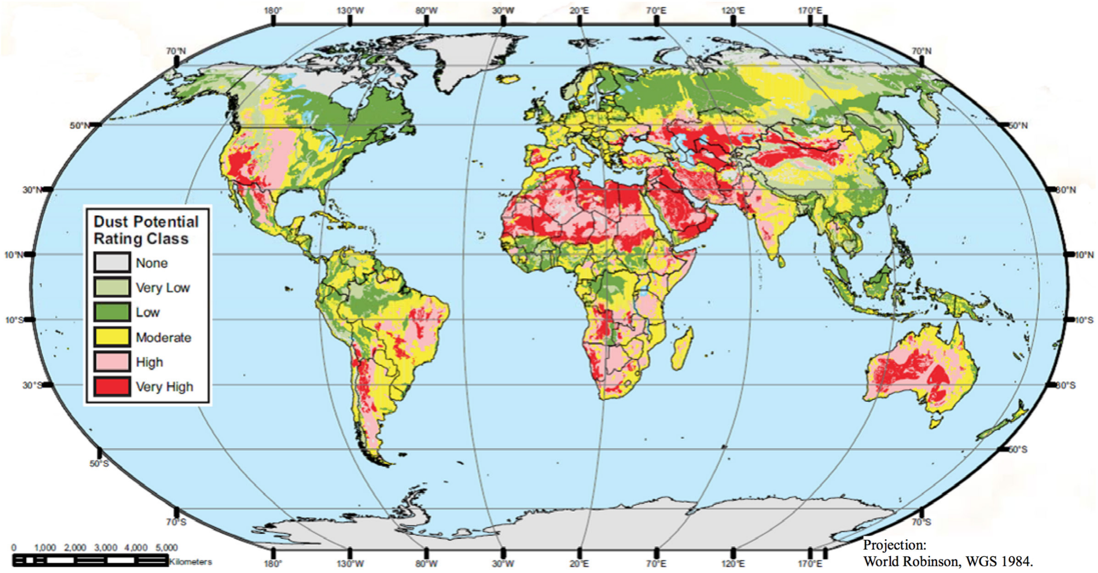
The specific objectives of the assessment are to:

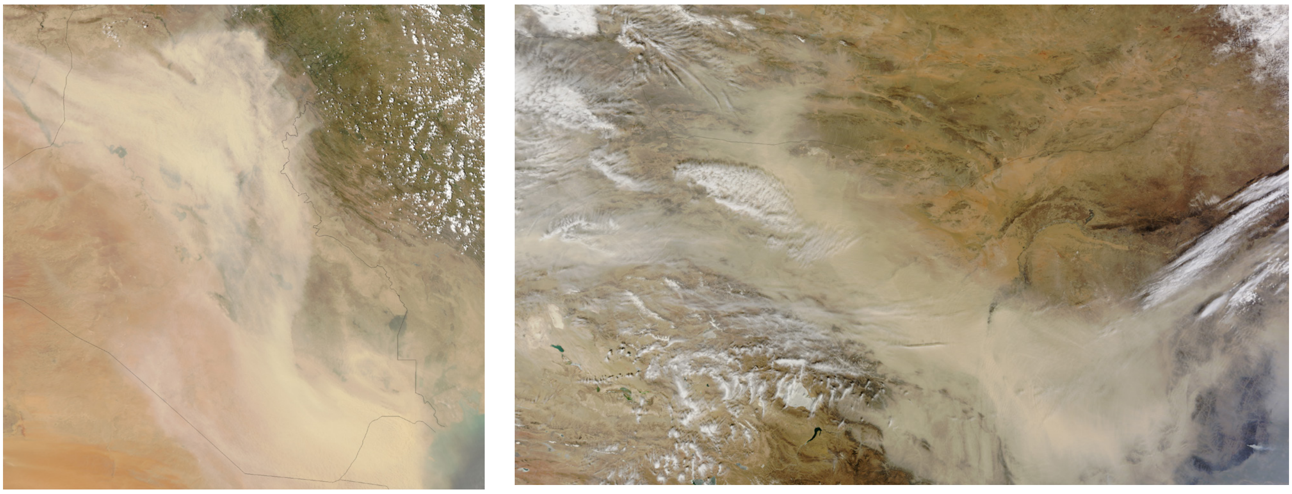
1. Synthesise and highlight the environmental and socio-economic causes and impacts of SDS, as well as available technical measures for their mitigation, at the local, regional and global levels.
2. Show how the mitigation of SDS can yield multiple sustainable development benefits.
3. Synthesize information on current policy responses for mitigating SDS.
4. Present options for an improved strategy for mitigating SDS at the local, regional and global levels, building on existing institutions and agreements.

The report first presents the science of sand and dust storm processes, which forms a foundation for technical and policy options for mitigating SDS. Section 2 describes the causes of sand and dust storms, their direct and indirect drivers and their inter-relationships. Section 3 provides an overview of SDS state and trends including global and regional characteristics and anthropogenic sources. Section 4 provides an overview of the environmental, social and economic impacts of SDS, including those on human health. Section 5 describes initiatives for monitoring and prediction and warning systems for SDS. Section 6 gives an overview of technical measures available for mitigating SDS at different scales. Section 7 provides an overview and examples of current national, regional and global policy initiatives before synthesizing the information from the preceding sections into a framework for policy action for mitigating SDS. The report also includes an appendix of case studies of regional and national actions and studies aimed at monitoring and mitigating SDS.

In this report we refer to mineral dust from the land surface and not to dust or aerosols from other sources: mineral dust makes up more than 50% of the global load of aerosol mass (Nenes *et al.* 2014). While the emphasis of the assessment is on SDS, wind erosion and aeolian transport may have significant impacts on soil and nutrient redistribution without producing SDS, with important impacts on agricultural production and land degradation. Therefore the report includes information on wind erosion processes, drivers and control measures, which are relevant to sustainable land management more generally. In addition the report covers the control of sand movement, which is a closely related aeolian process but which can occur in the absence of SDS.

Figure 1.1: Global Dust Potential Map. Source: DTF (2013).

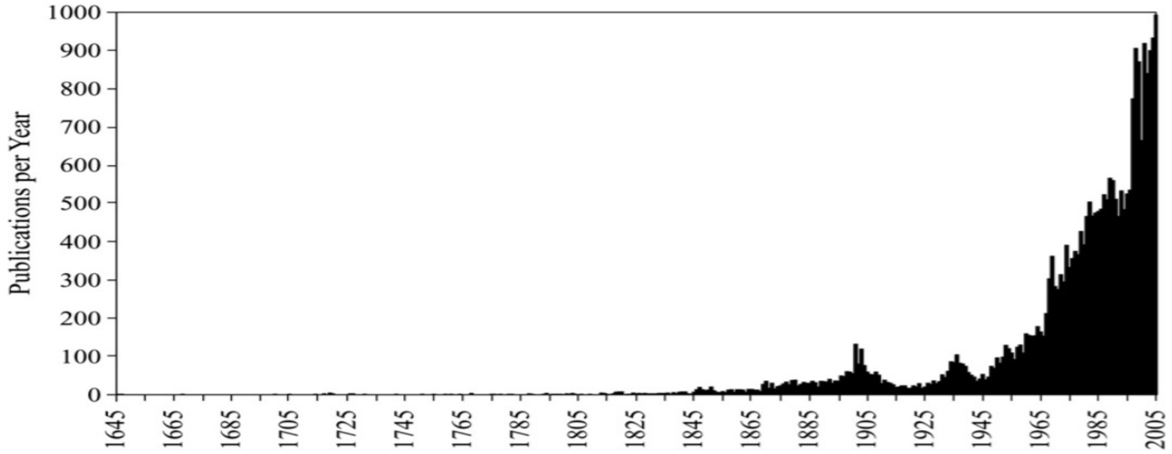




Dust storms extending from Syria and northern Iraq southward to Kuwait and Iran on 24 May 2012 (left) and along the China-Mongolia border on 9 March, 2013 (right). The extensive areas covered by the dust storms affected millions of people. Source: NASA images courtesy Jeff Schmaltz, LANCE MODIS Rapid Response team.

A dust storm hits a village in Golmud in the Qinghai Province of China near the Gobi desert in May 2010. Source: Mail online.

Figure 1.2: Time trends in publications on sand and dust storms derived from Google Scholar.
Source: Stout *et al.* (2009).



2. Sand and Dust Storms Processes

2.1 Sand and dust storm definitions

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 1000 m (McTainsh and Pitblado 1987). In this report we refer to mineral dust from the land surface and not to dust or aerosols from other sources, such as cosmic dust, sea salt, volcanic dust, or smoke particles. Definitions of the particle size of mineral dust vary, but here the range of <1 – 63 microns is used as a guide, which is approximately equivalent to the silt (2 – 63 microns) plus clay (<2 microns) size fractions in soils and sediments. Generally, the majority of particles transported more than 100 km from the source are <20 microns in diameter, in accordance with theories on settling velocity (Gillette 1979). However, there is an anomaly in that 'giant' sand-sized dust particles of even greater than 63 microns (i.e., sand grains) have been found thousands of kilometres from their source (e.g., Jeong *et al.* 2014; Middleton *et al.* 2001), although there is also a possibility of coagulation of particles during deposition.

There is not a strict delineation in the definition of sand versus dust storms, as there is a continuum of particle sizes in any storm. However, as a guide, sand size particles are larger than about 0.06 mm (60 microns). In storms dominated by sand (e.g., in sandy deserts), most of the particles will stay within several metres of the ground surface. Sand storms tend to be associated with low latitudes and have limited aerial extent.

For observations made at meteorological stations, there is a set of WMO synoptic codes for characterizing dust events (Goudie and Middleton 2006). The WMO also has definitions of *blowing dust*, when visibility at eye level is reduced but not to less than 1000 m; *dust haze*, which resides in the atmosphere from a previous dust storm; and *dust whirls*, which are whirling columns of dust moving with the wind.

Wind transport, or deflation, can cause particle movement through the processes of creep, saltation, and suspension. Particles larger than about 500 microns diameter will creep on the land surface.

Saltation is when wind transports particles of between 63 and 500 microns and usually at a height less than 1.5 metres above ground level. Suspension refers to longer range transport of particles of diameter of less than 63 microns (Pye 1987; Figure 2.1). Sandblasting is a process whereby saltating particles bombard soil aggregates, causing aggregate fragmentation and release of fine particles that are then entrained (Marticorena 2014; Shao 2008).

2.2 Sand and dust storm mechanisms

Sand and dust storms are atmospheric events that that result from the erosion and transport of mineral sediments from the ground surface. They are typically associated with arid and semi-arid (dryland) areas, but can occur anywhere where there are dry unprotected sediments (Goudie and Middleton 2006; Thomas 2011). The process involves three phases: the entrainment or emission of surface material, its transport through the atmosphere and its deposition (Figure 2.2).

Entrainment of particles occurs when the wind shear stress exerted on the surface (wind erosivity) exceeds the ability of the surface material to resist detachment or transport (sediment or soil erodibility). Wind erosivity is a product of wind velocity and wind flow characteristics, especially turbulence near the ground surface (Wiggs 2011a). In addition to ambient wind speed, vegetation and land form characteristics on surface roughness play a large role in determining wind erosivity (Giles *et al.* 2016; Table 2.1). Local wind conditions are also influenced by wind systems generated over larger areas, and thus may depend on land use and other physical factors in neighbouring regions.

Surface stability, or resistance to wind erosion, is dependent on the erodibility of the surface material and the degree of cover by non-erodible materials (e.g., rocks, plant litter, or snow cover; Table 2.1). It is important to note that most dust comes from mineral particle surfaces without soil formation, especially the dry surfaces of lake beds and playas (ephemeral lakes). Erodibility, in terms of susceptibility to wind erosion, is strongly dependent on the mineral composition and particle size distribution of the surface material and its moisture content.

Sediments that are most susceptible to dust storms tend to be associated with large basins of internal drainage with deep and extensive alluvial deposits, whereas sand dune systems are more associated with sand movement rather than as sources of fine-grained dust (Prospero *et al.* 2002; Thomas 2011). Erodibility is also dependent on soil structure and density, which are conditioned by soil organic matter and biological activity, and are highly sensitive to soil management (Bronick and Lal 2005). Soil physical (e.g., clay skins, gravel, salt) or biological crusts (e.g., caused by bacteria, algae, and mosses) also increase resistance to wind erosion (Dunkerley 2011). In some parts of arid zones, biological crusts provide an important protection mechanism, but are easily disturbed by anthropogenic activity such as vehicle traffic (Belnap and Gillette 1997).

The most frequent and severe dust storms are commonly associated with specific synoptic meteorological conditions that vary according to region. These include: (i) steep atmospheric pressure gradients around subtropical anticyclones, (ii) surface cyclones and their associated fronts, (iii) monsoonal airflows, (iv) local winds associated with strong gradients in relief, and (v) dust devils and convective plumes as a result of daytime turbulence in the planetary boundary layer, as well as near-surface cold-air outflows associated with thunderstorms, sometimes referred to as “haboobs” (see Knippertz 2014 for an overview).

Deposition distance from the source depends on the mass and shape of the particles, and factors such as wind speed and turbulence. Atmospheric dust may deposited through gravitational settling (dry deposition) and precipitation (wet deposition). There are strong regional differences in the proportion of dry or wet deposition. For example, in the Mediterranean region and the interior of China, dry deposition dominates, whereas deposition of Asian dust over the North Pacific is dominated by wet deposition (Zhao *et al.* 2003).

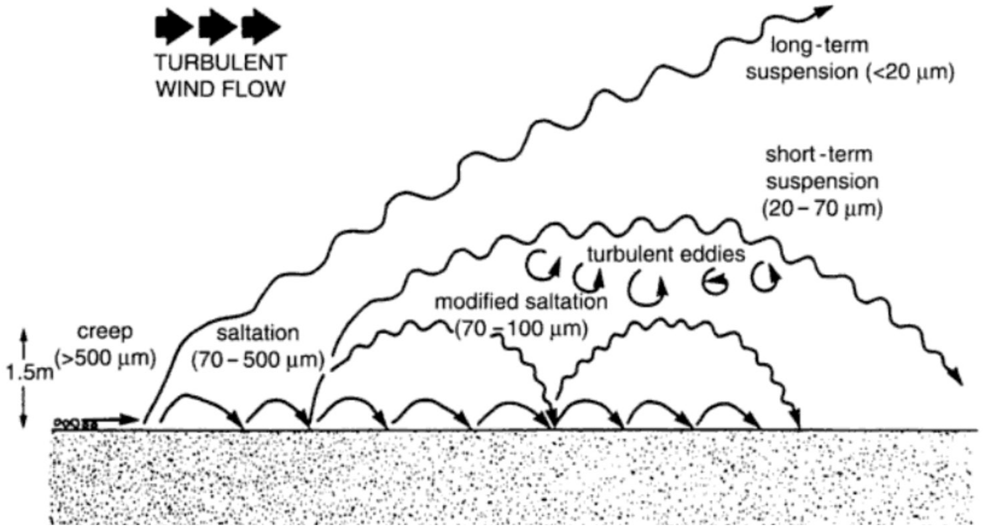
While most coarser transported materials are deposited within tens of kilometres of the source, dust storms are capable of transporting sediment over thousands of kilometres. Hence dust storms transcend political boundaries, which has important implications for their mitigation, since the effects are felt in different countries and even regions than their source of origin. For example, Saharan dust is transported to Amazonia, North America, Europe, the Middle East and China. Dust from Central Asia and China reaches Korea, Japan, the Pacific Islands and North America (Goudie and Middleton 2006). Dust from China has been identified as reaching the European Alps, after having been transported across the Pacific and Atlantic Oceans over 13 days, a distance of over 20,000 km (Grousset *et al.* 2003).

2.3 Causes of sand and dust storms

Sand and dust storms occur as a result of a series of interlinked direct (proximal) and indirect (distal) drivers operating at different scales. There are also strong feedback mechanisms both within and across scales. These inter-linkages have important implications for the mitigation of SDS.

There is need to distinguish drivers of SDS from natural sources, which supply most of the global dust emissions, and anthropogenic sources. Details on the relative importance of natural and anthropogenic dust sources are given in Section 3. However natural ecosystems are increasingly being subject to human pressure (MA 2005a), which may intensify their importance as source areas in future. In addition, human-induced climate change is a common driver in both natural and anthropogenic systems.

Figure 2.1: Particle transportation types. Source: Pye (1987).



2.3.1 Direct drivers in natural ecosystems

Wind is a main driver of sand storms and dust emissions in all systems. Specific synoptic meteorological conditions that produce winds vary in different regions (Section 2.2; Knippertz 2014).

A global review of trends in terrestrial near-surface wind speeds (McVicar *et al.* 2012) indicates that declines in wind speed are geographically widespread in recent decades, with declines being reported in the tropics and mid-latitudes of both hemispheres, but with increases reported at high-latitudes (i.e., >70° latitude). Lower wind speeds at low latitudes are expected to reduce SDS risk.

The activity of a dust source depends on the fraction of surface winds exceeding the erosion threshold defined by the local surface properties (Marticorena *et al.* 2014). It is high erodibility of surface material that defines most natural dust source areas, combined with aridity that limits the protective effects of vegetation cover. Hence most 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). These are described in more detail in Section 3, but examples are the Bodélé Depression of South central Sahara, West Sahara in Mali and Mauritania, and the Taklamakan Desert in the Tarim Basin in China (Washington and Wiggs 2011). Most of

Figure 2.2: A simplified depiction of sand and dust storm processes, controlling factors and impacts.
Source: Lu and Shao (2001).

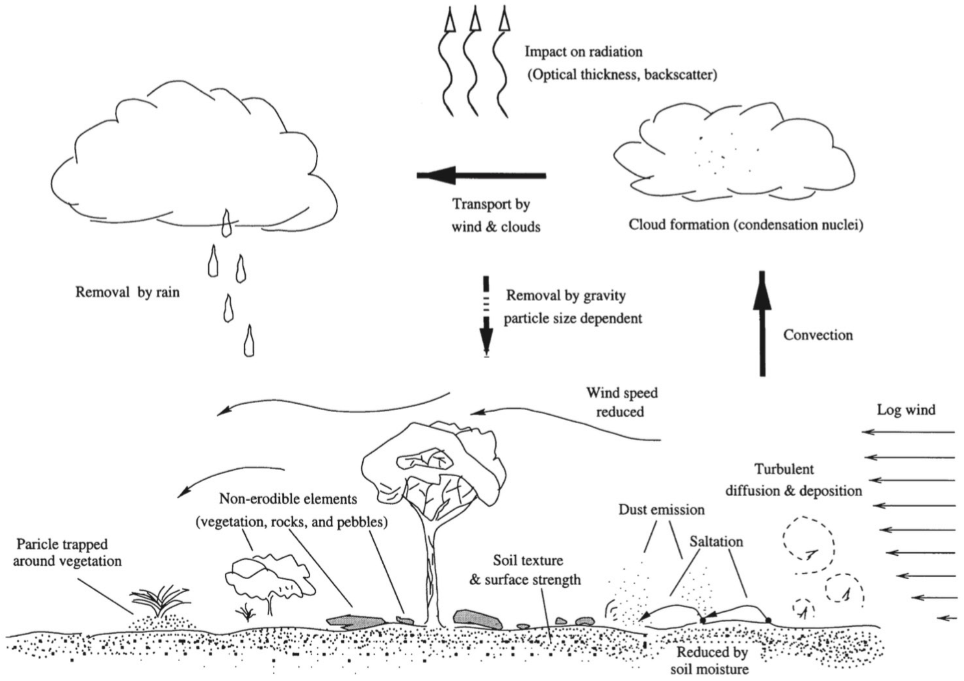


Table 2.1: Key physical factors influencing wind erosion. (Modified from Shi *et al.* 2004; Goudie and Middleton 2006).

Climate	Sediment or Soil	Vegetation	Landform
Wind speed (+)	Soil/sediment type	Type	Surface roughness (+/-)
Wind direction	Particle composition	Coverage (-)	Slope (-)
Turbulence (+)	Soil/sediment structure	Density	Ridge
Precipitation (-)	Organic matter (-)	Distribution (+/-)	
Evaporation (+)	Carbonates (-)		
Air temperature (+/-)	Bulk density		
Air pressure (+)	Degree of aggregation (-)		
Freeze-thaw action (+/-)	Surface moisture (-)		

(+) indicates that the factor reinforces wind erosion, whereas (-) indicates that the factor has a protective effect, reducing wind erosion. (+/-) indicates the effect can be positive or negative depending on the processes involved.

Protective lichen crusts on gravel plains in the Namib Desert. Excessive or unconfined vehicle tracks disrupt protective crusts in natural ecosystems. Photo credit: Jennifer Lalley, University of Johannesburg.

the dust generated from the Bodélé Depression comes from large exposures of a friable, low density deposit of diatomite (Washington and Wiggs 2011). On the other hand, the Taklaman Desert is characterised by smooth surfaces with dry, sandy soils, which also have low erosion thresholds (Marticorena 2014).

Bullard *et al.* (2011) identified seven geomorphic types that are commonly found in arid and semi-arid regions, which differ in terms of surface characteristics influencing their susceptibility to aeolian erosion, and which can be readily identifiable using remotely sensed information (Table 2.2). Ephemeral lakes and dry lakes with unconsolidated sediments have high risk of dust emission. Over long periods, selective removal of fine particles may lead to depletion of erodible material unless replenished by external sediments. Renewal of sediments is one reason why ephemeral water bodies are often important dust sources. In unarmoured, high relief deposits significant dust emissions only occur after periodic rains bring fresh sediment into the system. Unincised, low relief deposits allow replenishment of sediments and can generate significant emissions.

Sand sheets are areas of low relief sandy deposits. The size and sorting of the sediments makes them susceptible to wind erosion but, in many cases, wind erosion is limited by vegetation, coarse sands or shallow water tables (Bullard *et al.* 2011). Aeolian sand dunes are a wind-worked deposit with distinct relief. The contribution of sand dunes to dust emissions depends on type, activity level, and palaeo-environmental history. Large, more stable or older dunes may accumulate fines within the dune structure, but active, young or small sand dunes with a relatively rapid turnover of sand are unlikely to be major or persistent dust sources because they contain little fine material (Bullard *et al.* 2011). On the other hand, disturbance of older dunes will increase risk of dust emission. Mobile dunes do however pose a risk to human welfare when they occur in proximity to infrastructure, both from sand storms and sand movement. Any reduction in vegetation cover — by unsustainable harvesting, cultivation, grazing, burning, or even by drought — may lead to dune destabilization (Middleton 2011).

Loess is a depositional landform of primarily aeolian origin that is principally comprised of silt-sized sediments (Thomas 2011). Loess can become a significant dust source during periods of reduced vegetation or disturbance (Bullard *et al.* 2011). In addition to geomorphic type, the degree of connectivity with adjacent landforms also affects potential for dust emissions by influencing sediment supply and the supply of salts. The global distribution of aeolian deposits, including mobile dunes and loess deposits, are shown in Figure 2.3.

Human intervention in the hydrological cycle around ephemeral lakes and playas may accelerate desiccation, lower water tables, reduce soil moisture, and reduce vegetation cover, thus exposing susceptible sediments to wind erosion (Gill 1996) Examples are given in the following section.

In summary, the largest direct threat to natural systems is human disturbance in or around areas with high susceptibility for dust emission. Removal of vegetation, loss of biodiversity, and disturbance of the sediment or soil surface (e.g., through destruction of biological crusts or exposure of erodible sub-surface sediments), will increase susceptibility to dust generation in these areas. Human-induced hydrological changes that lead to desiccation of wet or ephemeral water bodies also increases SDS risk. Protection of natural ecosystems that are potential dust sources is therefore advisable.

2.3.2 Indirect drivers in natural ecosystems

Although there is currently much uncertainty on the magnitude of human activity on SDS, disturbance of natural systems through human pressure is highly likely to increase in the coming decades, including through human-induced climate change. A number of indirect drivers of desert degradation have been identified (Table 2.3). There has been increasing interest in reversing the negative effects of drivers in desert ecosystems through green economy, with the objective of sustainable use using modern technology and innovative water saving strategies to promote areas such as renewable energy, irrigated agriculture, desert cities, and eco-tourism (UNEP 2006; 2015b).

Climate change effects may go beyond increased dust emissions. For example, studies suggest that sand dune fields across southern Africa are likely to be reactivated (the sand will become significantly exposed and move) as a consequence of twenty-first century climate warming (Thomas *et al.* 2005).

Disturbance of hydrology around ephemeral lakes and playas is often due to demand for water resources for urban areas or irrigation. The development of roads and communication lines that block or divert inflow of drainage waters is another contributor to playa desiccation (Gill 1996). A global review of desiccated playas as a result of human activity found the most frequent occurrences were in the western US, especially in California (Gill 1996). A large scale example is the desiccation of the Aral Sea (Micklin 2007; see Section 3.2.2).

2.3.3 Direct drivers in human-dominated ecosystems

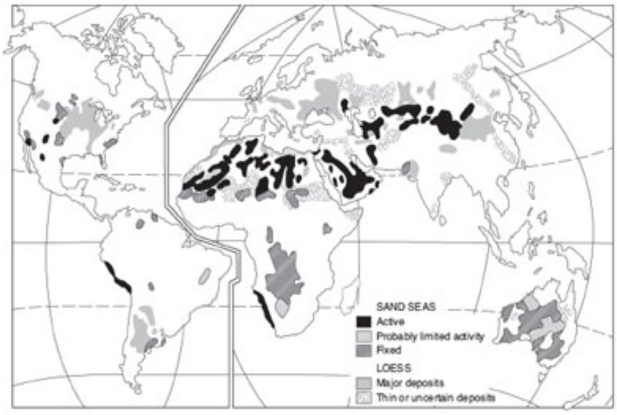
While most dust emission comes from natural sources, particularly dry lake beds which have little vegetation or human activity, wind erosion is an important problem in human-dominated systems and contributes to SDS. Globally as much as 32 million km^2 of land is susceptible to wind erosion, with 17 million km^2 having high or very high susceptibility (Eswaran *et al.* 2001). In these situations, decrease in vegetation cover is an important risk factor for wind erosion and SDS. This is because vegetation (i) increases wind velocity, (ii) exposes surfaces, (iii) usually makes surfaces less stable, and (iv) reduces trapping of sand and dust particles (Middleton 2011). Vegetation provides a mechanical barrier, controlling wind flow and reducing surface shear stress at the ground surface. Semi-permeable barriers are more effective than solid barriers as they reduce turbulence on the leeward side of barriers (Bird *et al.* 1992; Giles *et al.*

Table 2.2: Typology of geomorphologies in terms of contributions to dust emissions. Summarised from Bullard *et al.* (2011).

Geomorphic type	Typical texture	Importance for dust emission
Lakes		
Wet	Sand, Silt, Clay	Low
Ephemeral	Silt, Clay	High (if sandblasting) – Medium
Dry, consolidated	Silt, Clay	Low
Dry, non-consolidated	Silt, Clay	High (if sandblasting) – Medium
High Relief Alluvial Deposits		
Armoured, incised	Mega-gravel, Gravel, Sand	Low
Armoured, unincised	Mega-gravel, Gravel, Sand	Low
Unarmoured, incised	Gravel, Sand, Silt, Clay	Medium
Unarmoured, unincised	Sand, Silt, Clay	Medium - High
Low Relief Alluvial Deposits		
Armoured, incised	Gravel, Sand	Low
Armoured, unincised	Gravel, Sand, Silt, Clay	Medium
Unarmoured, incised	Sand, Silt, Clay	Low
Unarmoured, unincised	Sand, Silt, Clay	Medium
Stony Surfaces	Gravel, Sand, Silt, Clay	Low
Sand deposits		
Sand sheet	Sand	Low to medium
Aeolian sand dunes	Sand	Low to high
Loess	Silt, Clay	Low – medium
Low emission surfaces: bedrock, rocky slopes, duricrust, snow/ice permanent cover	Mega-gravel, Gravel, Sand, Silt, Clay	Low

Armoured = surface protected by cemented or hard layer, or gravels. Incised = channel incision.

Figure 2.3: The global distribution of aeolian deposits. Source: Thomas (2011).



2016). The distance over which barriers reduce wind speed is proportional to their height: typically, wind is reduced by 50% for up to 20 times the height of the barrier (Skidmore 1986). Landscape management practices that remove forest and woodland fragments or corridors, and reduce density of scattered trees and hedgerows in farmlands, will increase wind velocity as well as reduce the entrapment of airborne particles. Poor standards of crop management (e.g., related to soil fertility, seed quality, tillage, planting, and pest and disease control) that result in poor vegetation growth and soil cover increase risk of wind erosion. Technical measures for controlling wind erosion are further covered in Section 6.

Decrease in vegetation cover reduces the amount of plant litter returned to the ground surface and thereby increases surface exposure. Any management practice that removes or disturbs organic layers at the soil surface also increases surface exposure to wind. For example, ploughing for crop production or destruction of biological crusts through vehicular traffic disrupts the surface organic layer. Return of organic matter to the soil from vegetation also plays an important role in maintaining soil stability and reducing soil erodibility (Bronick and Lal 2005). Organic inputs to soil are important for maintaining soil structure and biological activity, which increase effective particle size through aggregation and increase resistance to detachment.

Degradation processes are collectively referred to as land degradation—the long-term loss of ecosystem function and services, caused by disturbances from which the system cannot recover unaided (UNEP 2007). Land degradation is driven by unsustainable land use and management practices (Box 2.1). When individual land degradation processes, acting locally, combine to affect large areas of drylands, desertification occurs (UNEP 2007). Desertification is formally defined by the UN Convention to Combat Desertification (UNCCD), as land degradation in arid, semi-arid and dry sub- humid areas resulting from various factors, including climatic variations and human activities (UNGA 1994). Desertification is a driver of wind erosion and SDS due to the development of degraded and exposed, dry surfaces over large dryland areas, with a long wind fetch.

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). Increased exposure to wind erosion results in preferential removal of silt, clay and organic matter components of the soil, which reduces soil fertility, physical condition and water storage capacity. Reduced soil health in turn further reduces vegetation growth, which further increases vulnerability to wind erosion. Changes in vegetation distribution can also impact sediment transport rates and dust emission.

There is a strong interaction between vegetation cover, soil management and the erodibility of the soil or surface. The critical level of vegetation cover needed to protect the soil against wind erosion increases with soil erodibility. Soils with finer particle size and poor structural stability are most erodible, especially soils with a high content of silt or very fine sand (Borselli *et al.* 2012; Le Bissonnais 2016). Cultivation of sensitive soils is a common cause of land degradation and exposure of land to wind erosion. Failure to consider the potential of land and sensitive soil types has resulted in many disastrous development schemes, including attempts to cultivate the drier portions of the midwestern United States that resulted in the Dust Bowl; the overstocking of rangeland in the southwestern United States that caused region-wide transitions of grasslands to shrublands with low forage value; and the huge East African groundnut scheme which attempted to convert rangelands to mechanized peanut production agriculture (referenced in Herrick *et al.* 2016).

Dry soils are much more erodible by wind than moist soils, which is one reason dust storms are strongly associated with drier climates. However, dust storms can occur even in cold climates, for example from outwash plains in Iceland (Dagsson-Waldhauserova *et al.* 2014), deltas in Alaska (Seppälä 2004), and tailing dumps on the Kola Peninsula in the Russian Arctic (Mesyats and Volkova 2009).

Table 2.3: Indirect drivers of desert degradation. Source: UNEP (2006).

Driver	Examples
Population pressure	Although population pressure is low in desert areas, population growth along rivers, oases and at desert margins pose a threat.
Investment and capital	Investment in resource extraction (oil, gas, iron, uranium, phosphates, nitrates, and copper, among other minerals) creates pressures on deserts and may increase as more readily reserves are depleted. Desert tourism has steadily increased and is expected to continue to do so. Military testing sites are often located in deserts.
Globalization	There is a risk of globalization contributing to increased inequity in deserts leading to unrest.
Climate change	Climate change projections vary widely among regions but deserts will be particularly vulnerable to small changes in climate.
Energy	As the costs of solar and wind energy start to compete with fossil fuels, utilization of deserts for solar and wind farms could increase.
Ecosystem collapse	Historically there are many examples of collapses of desert societies through salinization as a result of irrigation schemes or water overuse, including more recent examples such as the Aral Sea in central Asia and the Tarim Basin in China.

2.3.4 Indirect drivers in human-dominated ecosystems

Because wind erosion and SDS in human-dominated ecosystems are strongly related to degradation of vegetation, soil properties and hydrology, they are affected by indirect drivers of land degradation, especially desertification (Box 2.2). Land degradation impacts on climate change may also feedback to affect SDS, which is covered in the next section. Large area and long-term preventive strategies for reducing land degradation will need to focus on the indirect drivers and risk factors (Shepherd *et al.* 2015). However, the importance and even the direction of the effect of these drivers on sustainability of land use and land degradation vary with local circumstances (D’Odorico *et al.* 2013; Geist and Lambin 2004; Mirzabaev *et al.* 2016).

A meta-analysis of drivers of desertification (Geist and Lambin 2004) found that there is a suite of six recurrent clusters of underlying drivers, namely demographic, economic, technological, climatic, policy and institutional, and cultural factors; which operate on a set of four clusters of direct drivers, which are agricultural activities, infrastructure extension, wood extraction and increased aridity (Figure 2.4).

Climatic factors were the most common driver in the above meta-analysis. Human pressure on land during extended drought periods has been a major factor behind dust bowl catastrophes (see Section 2.4). Climate change is an important potential driver of future wind erosion and SDS risk, especially the occurrence of more extreme wind events and movement to drier climates, but reverse effects are also possible. Regions that are currently dusty areas and which are likely to become drier include most of the Mediterranean areas of Europe and Africa, northern Sahara, central and west Asia, southwest USA, and southern Australia (Christensen *et al.* 2007; IPCC 2013). Precipitation has increased in mid-latitude land areas in the Northern Hemisphere since 1950 (IPCC 2013), which might help to reverse desertification in the mid-latitude belt. Dusty regions that are likely to become wetter include eastern Africa and east Asia, whereas large model uncertainties preclude projections for the Sahel-Sudan, the Gangetic basin and the Lake Eyre region (Christensen *et al.* 2007; IPCC 2013).

Wind erosion on unprotected cultivated field. Source: Ministry of Agriculture, Food and Rural Affairs, Ontario, Canada.

Climate forcing may result in increased land use pressure on marginal lands (Ward *et al.* 2014) and improvement in sustainable land management practices may be important to mitigate these effects. There are major feedback mechanisms between climate, vegetation and dust (d'Odorico *et al.* 2013). Vegetation changes affect precipitation recycling and surface energy balance, which in turn influence dust emissions from landscapes, which feedback on to climate (see Section 2.3.5). At a global level, modelling studies of climate change impacts on global dust emissions show a wide range of potential effects, ranging from relative small changes (+/–20%) (Tegen *et al.* 2004) to large decreases (–20% to –60%) (Mahowald and Luo 2003) to very large increases (+200%) (Woodward *et al.* 2005). In the latter study, coupled-carbon cycle modelling predicts the drying up of the Amazon.

Using model simulations from 17 climate and equilibrium vegetation models, Mahowald (2007) estimated changes in desert dust source areas due to climate change and carbon dioxide fertilization (Figure 2.5). Without carbon dioxide fertilization, the mean of the model predictions indicated that desert areas would expand from the 1880s to the 2080s, due to increased aridity. If carbon dioxide fertilization was allowed, the desert areas became smaller. There was large variation in results among the different models but the results indicate that a better understanding of carbon dioxide fertilization is important for predicting desert response to climate.

In the meta-analysis of Geist and Lambin (2004), after climatic factors, technological factors were the most common group of drivers (69% of cases). Interestingly technological innovations, such as improvements in land and water management through motor pumps and boreholes or through the construction of infrastructure related to water management (e.g., dams, reservoirs, canals, collectors, drainage), were often a driver of degradation even when successfully implemented. This was due to factors such as increased water loss and changes in hydrological cycles.

The study found that institutional and policy factors were behind 65% of the reported cases of desertification. Modern policies and institutions were to blame as often as traditional institutions. The introduction of new land tenure systems, whether under private (individual) or state (collective) management, especially in developing regions, was a significant driver.

Economic drivers (79% of cases) were due to market growth and commercialization on the one hand, and economic depression and impoverishment on the other hand, often expressed through boom and bust cycles. Where population pressure was a cited as a driver (73% of cases), this was often linked to the immigration of cultivators into rangelands or regions with large-scale irrigation schemes, or of herders into marginal sites, rather than due to high fertility rates of impoverished rural groups. War, insurgency, and violent conflicts were identified as a driver in 8%

Box 2.1: Land use and management practices that increase risk of wind erosion

- Deforestation and forest degradation, especially of dryland woodlands
- Rangeland degradation; overgrazing
- Over-exploitation of vegetation resources in deserts
- Off-road vehicle use and construction activities in deserts
- Wild fires
- Removal of natural wind barriers in landscapes (hedgerows, tree lines, forest/woodland fragments)
- Tillage or disturbance of highly erodible soils
- Poor crop management practices that result in low vegetation cover of soil
- Removal of organic residues from the land as opposed to maintaining mulch or litter layers or returning residues to the soil
- Poor irrigation practices that lead to salinization and land abandonment
- Land use and water management practices (including water diversion and abstraction) that result in undesirable hydrological changes
- Mining and other industrial operations that leave disturbed land with low vegetation cover (e.g., tailing dumps, mining and ore-enrichment activities)

Desertification occurs when local land degradation processes, usually driven by unsustainable land management practices, combine to affect large areas of drylands. Photo credit: Gemma Shepherd, UNEP.

of the cases, but are expected to have increased in importance in Africa and West Asia since the time of that review (Geist and Lambin 2004).

A more recent global and regional analysis of land degradation drivers Mirzabaev *et al.* (2016) found broad agreement with the above meta-analysis. Sustainable land management (SLM) was found to be positively associated with higher population density when combined with good socio-economic development, strong rule of law, secure land tenure, and absence of crop agriculture.

Common sets of global biophysical and socioeconomic causes and symptoms of environmental degradation have also been conceptualized as syndromes, or patterns of processes relating human activities and environmental changes (Schellnhuber *et al.* 1997). A number of desertification syndromes have been identified (Downing and Lüdeke 2002), of which several are relevant to SDS, defined in Table 2.4, although there may be some overlap between them (e.g., over-exploitation and dust bowl syndromes). Other syndromes relevant to SDS may include the Scorched Earth syndrome (mass tourism), which is land degradation through development and destruction of nature for recreation, for example in deserts; and land degradation through war and military action.

The Sahel Syndrome is found in large areas of Latin America, Sub-Saharan Africa, in arid zones of Northern Africa and Asia as well as South and East Asia (Lüdeke *et al.* 2004). The Dust Bowl, Overexploitation and Aral Sea syndromes prevail in industrialized countries. The desiccation of the Mesopotamian marshlands as a result of dam building along the Euphrates and Tigris rivers and installation of drainage schemes (UNEP 2001) is another example of the Aral Sea syndrome. The Dust Bowl Syndrome dominates in Europe, the former Soviet Union and the United States, and is the most widespread syndrome in temperate as well as more arid zones in Spain and the Western USA (Lüdeke *et al.* 2004).

Box 2.2: Indirect drivers of land degradation.

- Population increase and economic globalization leading to increased demands for food, feed, and other products
- Failure of policy to recognize non-economic ecosystem functions
- Policies that unwittingly encourage unsustainable land management (e.g., Geist and Lambin 2004)
- Land use change to less sustainable uses
- Use of prime agricultural land for urban development and waste disposal, thereby increasing pressure on marginal land
- Subsistence farming
- Lack of access to rural credit, extension services and markets
- Poverty
- Insecure land tenure
- Migration to fragile land
- Climate change
- Other risk factors: topography, climate, soil erodibility
- War and insecurity

Figure 2.4: Drivers of desertification. Indirect drivers (lower six clusters of factors) operate on direct drivers of desertification (upper four clusters of factors). Source: Geist and Lambin (2004).

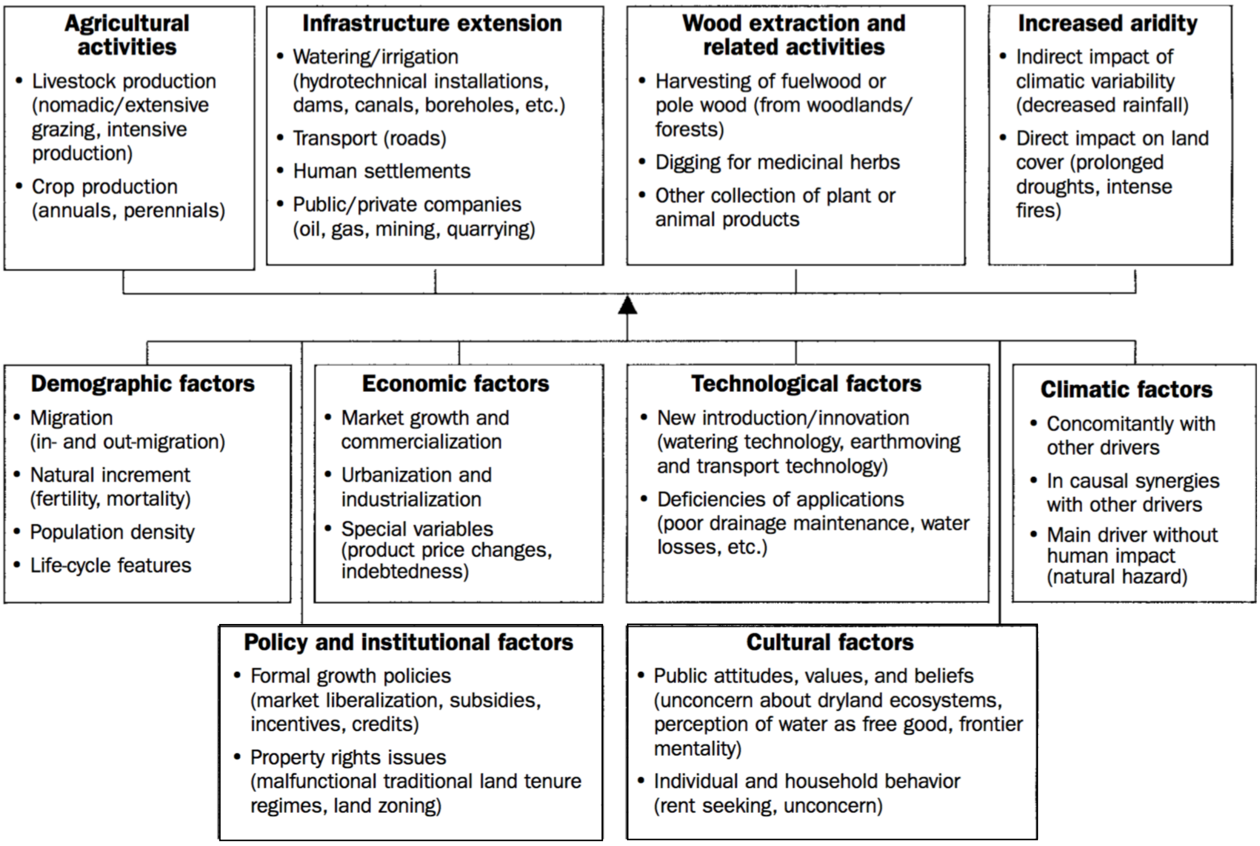
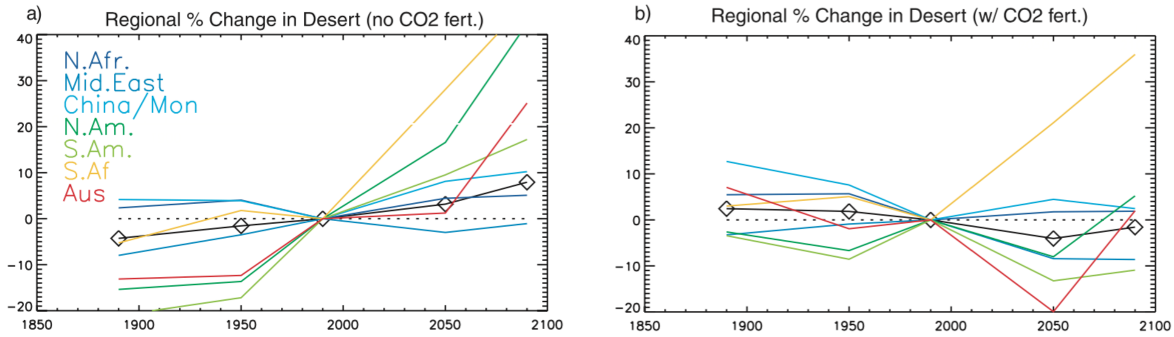


Figure 2.5: Regional changes in desert area from the mean of the models for the case of (a) no carbon dioxide fertilization and (b) with carbon dioxide fertilization. Source: Mahowald (2007).



2.3.5 Land degradation feedback processes

Of particular importance for human-induced SDS are feedback mechanisms between land degradation and climate (Figure 2.6). Land degradation contributes to climate change through production of greenhouse gases (GHGs), changes in surface energy balances and direct impact on dust increase. Climate change, especially in drylands, can cause increase in frequency, duration and intensity of droughts and dust storms, forcing further climate change (Arimoto 2001).

Sustainable land management has a role in climate change mitigation, and hence reduced risks of future acceleration of wind erosion and dust events. Carbon stored in vegetation and soils accounts for about 40% of the global carbon stock, but is released when vegetation is cleared and burned and when soil organic matter is mineralized (MA 2005b). Emissions of GHGs from agriculture, land use, land use change and forestry account for about one quarter (~10–12 Gt CO_2eq yr^1) of all global GHG emissions, and so land degradation, or reversing it through SLM, plays a major role in global climate change (IPCC 2014a). Land degradation both reduces carbon stocks in vegetation and soil and reduces the potential of soil to store carbon. In addition to CO_2 emission, other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), are emitted as a result of the conversion of forests to agricultural lands.

Deforestation and conversion of land to pasture or cropland can impact on other atmospheric components leading to consequences for the local, regional and global climate (Figure 2.7). Generally, vegetation reduction (including naturally during drought periods) increases surface albedo and the ratio of convective sensible heat transfers to latent heat transfers from the surface to the atmosphere. It also reduces aerodynamic roughness leading to less mechanical mixing of the atmosphere in the boundary layer, and reduces evapotranspiration leading to lower atmospheric moisture concentrations (MA 2005b; ODG 2006; WMO 2005b).

Dust also affects climate through various direct and indirect mechanisms, including through its effect on (i) the carbon cycle through the redistribution of soil organic carbon and as a moderator of carbon sources and sinks, (ii) marine primary productivity and surface ocean cooling, and (iii) radiative effects (Park *et al.* 2005; Goudie and Middleton 2006; Washington and Wiggs 2011). Atmospheric dust affects air temperatures through the absorption and scattering of solar radiation.

Due to their composition and size, dust aerosols perturb the Earth-Atmosphere system's energy budget through their direct interaction with the shortwave and longwave radiation, and reduce the development of the planetary boundary-layer (Pérez *et al.* 2006). The pathways by which aerosols can affect clouds represent one of the largest uncertainties in understanding the climate forcing (Kaufman *et al.* 2005). Rainfall may be affected as a result of dust effects on changes in atmospheric temperatures and in concentrations of potential cloud condensation and ice nuclei, which affect convectional activity and cloud formation (Nenes *et al.* 2014). There is evidence that dust can in some situations inhibit precipitation (Rosenfeld *et al.* 2001). The detrimental impact of dust on rainfall is smaller than that caused by smoke from biomass burning or anthropogenic air pollution, but the abundance of desert dust in the atmosphere renders it important.

Dust-induced climate change that results in increased drought or more extreme wind conditions will cause further increase the frequency and intensity of sand and dust storms. On the other hand, cooling due to dust may partially obscure the warming that is attributed to increasing greenhouse gases (Miller and Tegen 1997). Evidence from loess deposits of China and other parts of the world, ice cores, lake sediments, and ocean cores indicates that dust storm activity in the past, especially during the Last Glacial Maximum during the Quaternary, has been substantially greater than at present, varying at decadal timescales in response to climate and human influence (Cowie *et al.* 2013; Goudie and Middleton 2006). Dust as a contributory factor to climate change is now being built into numerical climate models (e.g., Mahawold *et al.* 1999; Tegen at al 1996), although these models do not yet

Table 2.4: Examples of syndromes related to desertification and sand and dust storms. Modified from Downing and Lüdeke (2002); Lüdeke *et al.* (2004).

Syndrome name	Underlying functional pattern	Syndrome description	Pre-disposing factors
Sahel	Subsistence-oriented smallholder agriculture	Downward spiral by mutual reinforcement of resource degradation and impoverishment	Marginal land; no alternative income sources
Over-exploitation	Extraction of renewable resources	Vegetation and soil degradation due to profit-orientated overuse of renewable resources, mainly forests and dryland woodlands; policy failures in stopping or regulating the exploitation	Accessibility and usability of forests and dryland woodlands; national dependency on wood export
Dust bowl	Profit-orientated capital-intensive agriculture	Soil and environmental degradation due to capital-intensive, profit-orientated overuse and extensive application of chemicals; decreasing labour intensity and/or land pressure on smallholders	Profitable soil or pasture conditions; accessibility by train/road/ship; sensitive soils
Aral sea	Centrally-planned large-scale water schemes	Environmental degradation. Socioeconomic problems, and international conflicts caused by dams and irrigation schemes	Tendency towards top-down project planning and purely technological solutions

have the ability to simulate with confidence dust-environment interactions and the response of African dust to future climate change (Evan *et al.* 2014).

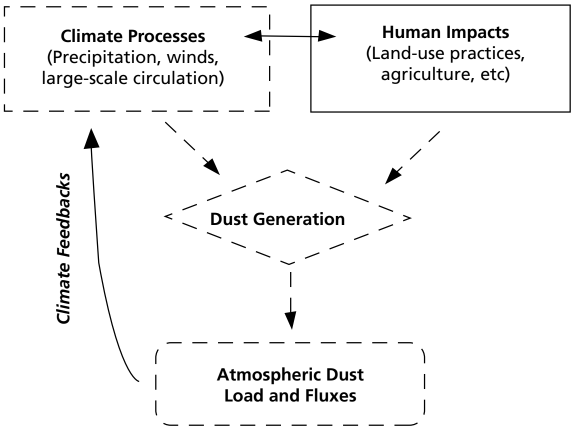
Mixing of dust aerosols with ammonia emissions from agriculture and acidic aerosols from fossil fuel burning may change the chemical and optical properties of dust, which in turn may affect its interactions with radiation, cloud microphysics and biogeochemical cycles (Ginoux *et al.* 2012). On the other hand, natural dust loading may be reduced by 60% if carbon dioxide levels double due to fertilization effects on vegetation (Mahowald *et al.* 2006). There are also possible feedback effects from dust suppressing precipitation (Rosenfeld *et al.* 2001) or from changes in regional circulations (Miller *et al.* 2014).

In summary, the multiple feedbacks between anthropogenic dust emissions, climate and both terrestrial and ocean biogeochemical cycles make it difficult to predict the impact of increased anthropogenic dust emissions on the balance in the Earth system. Accelerated land degradation, especially in dryland areas, could lead to rapid unpredictable and undesirable changes, and so precautionary principles should be applied. The key to containing anthropogenic dust emissions is through sustainable management of all land uses and water across whole landscapes including both natural and human-dominated ecosystems. To achieve sustainable management at scale will require acting on the indirect, or distal drivers of land degradation.

2.4 Contribution of human activities to dust storms

Although there are sound theoretical reasons, presented in the above sections, why human-induced land degradation and/or climate change should have contributed to changes in the frequency and severity of SDS in some regions, it is difficult to quantify these effects based on primarily modelling results due to the many confounding factors involved (Prospero *et al.* 2002; Tegen and Fung, 1995; Tegen *et al.* 1996; Luo *et al.* 2003; Tegen *et al.* 2004; Mahowald *et al.* 2004; Zender *et al.* 2004; Woodward *et al.* 2005). For example, cause and effect can be geographically and temporally separated, such as in the case when hydrological changes induced by human activity cause desiccation of ephemeral rivers and streams, alluvial fans, playas, and saline lakes in arid areas, resulting in their conversion to significant dust sources (Gill, 1996). Nevertheless, the current evidence on anthropogenic contributions to SDS is presented below.

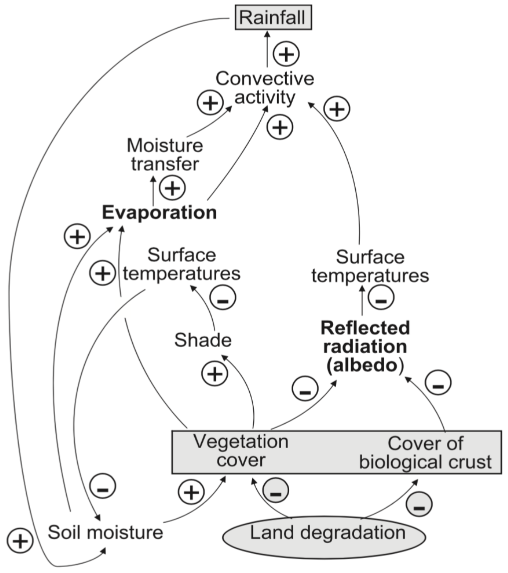
Figure 2.6: Dust – climate feedbacks. The impacts of human activities on atmospheric dust loads and the feedbacks to climate. Source: Arimoto (2001).



2.4.1 Current dust emissions

There is large uncertainty on the relative contribution of human action to current levels of dust emissions, with estimates ranging in various studies from <10% to 50% of current global emissions (Table 2.5). Those studies that considered sources from disturbed or degraded land give estimates of 10–50% (Sokolik and Toon 1996) and 30–50% (Tegen and Fung 1995) of the total atmospheric dust loading, but these disturbed sources include natural sediments or soils known to have been affected by shifts in land cover as a result of drought cycles. On the other hand, the studies that give estimates of <10% to 25% of global emissions only account for agricultural areas, and do not account for effects of human degradation in arid regions, for example playa desiccation. The more extreme upper and lower estimates in Table 2.5 may also be

Figure 2.7: Land degradation and climate regulating process (MA 2005a). Positive signs indicate enhancing effects, while negative signs indicate reducing effects.



attributed to model dependent errors or uncertainties (Mahowald *et al.* 2004).

The study by Ginoux *et al.* (2012), which uses estimates of dust optical depth derived from MODIS data used in conjunction with other data sets (2003–2009) including land use, estimates that 25% of the total annual global dust emissions of 1,536 Tg yr^{-1} is attributable to anthropogenic sources, principally agriculture, with the remaining 75% coming from natural dust sources.

There are large regional differences in the distribution of emissions between natural and anthropogenic sources (Figure 2.8). For example, North Africa produces only 20% of global anthropogenic emissions but accounts for 55% of the global total emissions, whereas 75% of Australia's dust is anthropogenic but accounts for only 13% of the global anthropogenic emissions (Ginoux *et al.* 2012).

In their combined satellite and model-based study, Ginoux *et al.* (2012) suggest that about 85% of all anthropogenic emissions are associated with hydrologic sources (water bodies that dry out during some periods). This relationship might be linked to the use of water resources for croplands, for urban use, and for grazing ranges for sheep and cattle. Because of this association, the activity of these sources could change greatly with changing climate. In contrast, natural sources are weakly related to ephemeral water bodies, with only 15% associated with presently ephemeral water bodies. This is because of the importance of paleolakes (i.e., lake beds that are currently permanently dry) as sources of aeolian dust (Ginoux *et al.* 2012).

There are many examples, collected from numerous countries, of the effects of anthropogenic land disturbance on dust emission and the desiccation of playas (Gill 1996). The expansion of livestock grazing in the early twentieth century is reported to have increased dust deposition by 500% in the western United States (Neff *et al.* 2008). Mining and related operations (e.g., tailing dumps, ore enrichment activities) can create dust sources (Amosov *et al.* 2014), including in areas far from drylands such as the Russian Arctic (see Figure 3.3).

The "Dust Bowl" drought of the 1930s, which was highly unusual for North America, was primarily forced by sea surface temperatures (SSTs) interacting with land use. Simulations using General Circulation Models (GCMs) can only reproduce the geographic distribution and intensity of the SDS, if forcing from human land degradation during the period is included (Cook *et al.* 2009). The GCM simulation of the drought was much improved when the new dust aerosol and vegetation boundary conditions were included as feedbacks on climate. The analysis concluded that human-induced land degradation is likely to have not only contributed to the dust storms of the 1930s but also amplified the drought, and these effects together turned a modest SST-forced drought into one of the worst environmental disasters in the history of the USA. Even today, cropland and rangelands are the main sources of dust in the southern high plains of North America (Stout 2001; Lee *et al.* 2012; Lee and Gill 2016).

A recent study suggests a similar pattern of cause and effect occurred in a south-eastern Australian Dust Bowl during 1895–1945. There was over-stocking of sheep and clearing for wheat cropping during this period, which coincided with a drought. The consequence was extreme erosion and sand drift and pronounced long distance dust transport to coastal cities (Cattle 2016).

Since the late 1800s, there have been reports of new dust sources created by water diversion for irrigation. Examples are Owens Lake in California (Cahill *et al.* 1996; Gillette 1999), the Aral Sea in Central Asia (Micklin 2007), and Lake Ebinur in northwest China (Abuduwaili *et al.* 2008). On the other hand, restoration and mitigation of degraded land have reduced dust activity from Lake Texcoco in central Mexico, Kara-Bogaz Gol in northwest Turkmenistan, and the Konya Basin in the central Anatolia Region of Turkey (Gill 1996). Further evidence for the effect of human activity on SDS is provided in the regional descriptions (Section 3.2) and from observations on the reduction in SDS when vegetation is restored in dryland areas (Section 7).

2.4.2 Limitations of estimates of anthropogenic sources

The large uncertainty in global anthropogenic sources be attributed to the lack of consistent and detailed characterization of dust sources with global coverage, but also to insufficient understanding of the various interacting processes (Prospero *et al.* 2002). Ginoux *et al.* (2012) identified the threshold of wind erosion under different land uses and moisture conditions as the principal source of uncertainty in their results. However there are also limitations in the sensitivity of the approach to detecting low concentrations of suspended dust at low altitudes and over spectrally similar surfaces, and in the use of land use data to attribute dust sources in the absence of information about actual management.

Table 2.5: Examples of estimates of the relative contribution of human activity to current levels of global dust emissions.

Source	Based on	Relative contribution
Tegen *et al.* (2004)	Agricultural areas	<10%
Stanelle *et al.* (2014)	Agricultural areas	10%
Sokolik and Toon (1996)	Disturbed area as proportion of total land area	20% (10 – 50%)
Tegen and Fung (1995)	Degraded lands	30 – 50%
Prospero *et al.* (2002)	Location of major source areas	Minor (<20%)
Ginoux *et al.* (2012)	Agricultural areas	25%

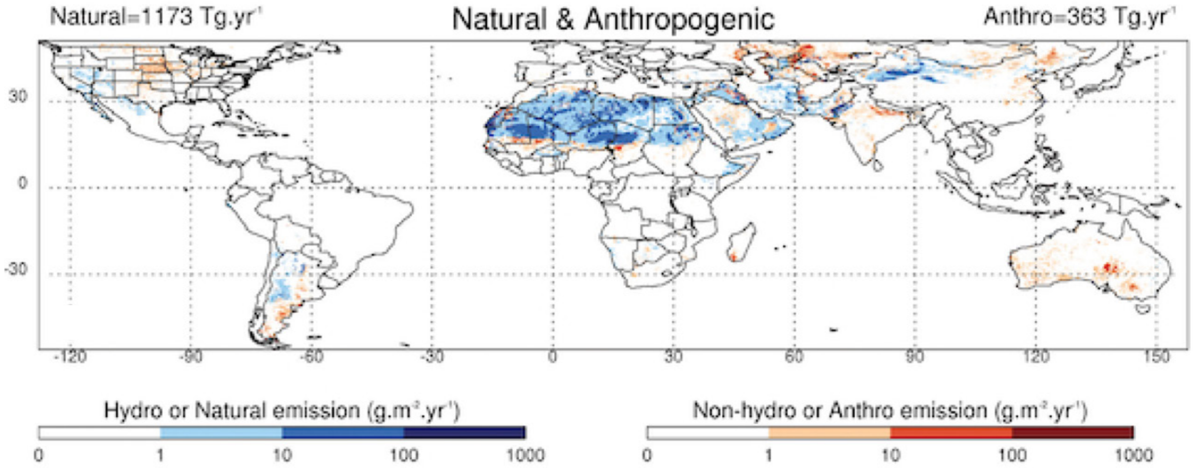
It should be noted that areas classified as anthropogenic dust sources are those located in an area actively managed by humans (identified from land cover data) but this does not mean that humans are necessarily the cause or a contributing factor to the dust emission. The latter will occur if the management activities push the condition of a landscape (roughness, soil erodibility) outside the range of natural variability that could be expected for a site given its ecological condition and the antecedent climate. On the other hand, desiccation of playas due to hydrological changes driven by human activity in adjacent areas, could be miss-classified as natural sources. More detailed, time series studies over time are required to establish human causes of SDS.

The sensitivity of the MODIS Deep Blue approach to low magnitude - high frequency events should also be scrutinized, particularly for areas which experience high rates of aeolian sediment transport (and land degradation), but which do not produce significant suspended dust loads - and which may therefore be omitted from this review.

2.4.3 Past and future dust emissions

In terms of historic contributions over the twentieth century, the limited paleodata available suggest a doubling of global dust loads in the due to anthropogenic activities and/or climate change over much of the globe (Mahowald *et al.* 2010). Stanelle *et al.* (2014) investigated the relative importance of climate change and anthropogenic land cover change for dust emissions and burden changes between the late nineteenth century and today. They used a climate-aerosol model (ECHAM6-HAM2) complemented by a new scheme to derive potential dust sources using vegetation cover that was able to distinguish between emissions from natural and agricultural dust sources. According to their simulations, global annual dust emissions have increased by 25% between the late nineteenth century and today. About 56% of this change was attributed to climate change and 40% to anthropogenic land cover change (e.g., agricultural expansion). There were however large regional differences (Figure 2.9). For example, present dust emissions were clearly dominated by climate change

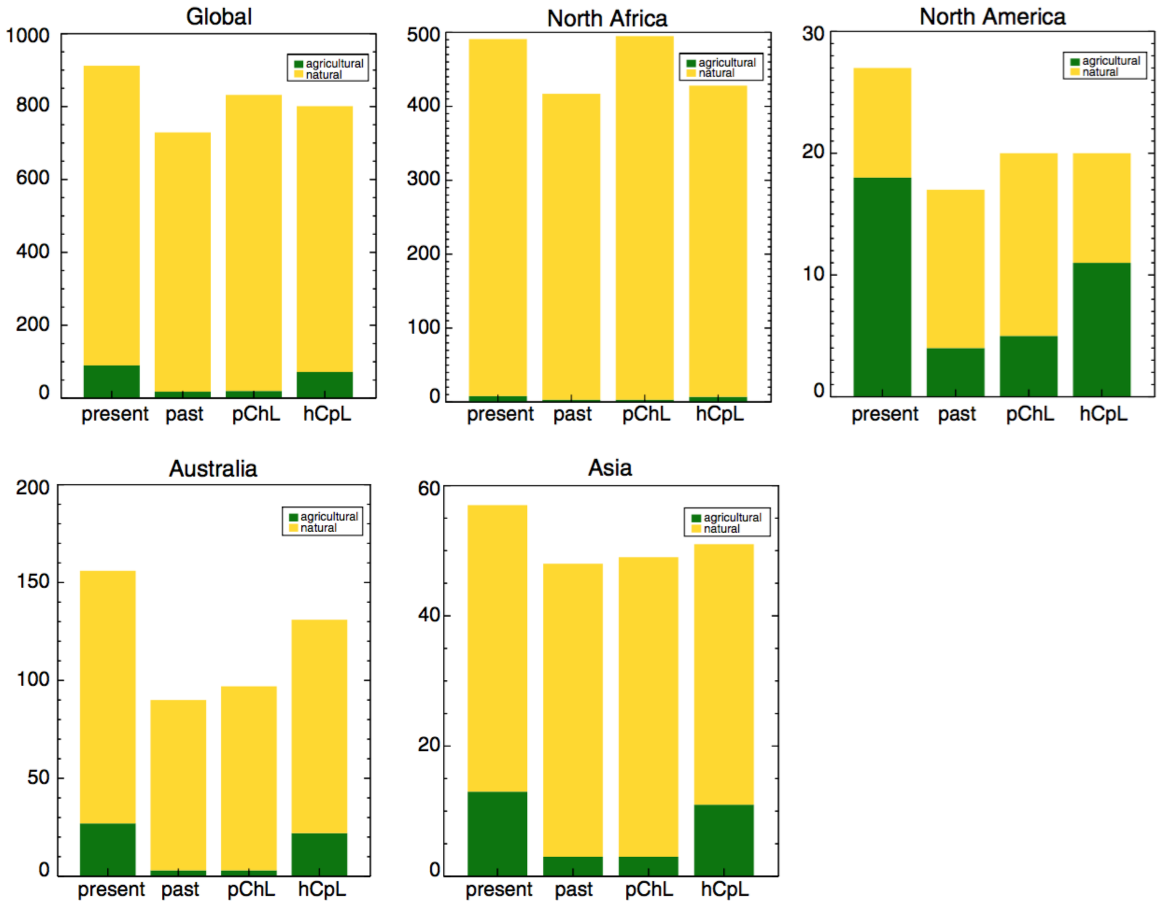
Figure 2.8: Annual mean dust emission from land use estimated from MODIS Deep Blue aerosol products (2003–2009). Hydrologic (Hydro) and natural sources are in blue and nonhydrologic (Non-hydro) and anthropogenic (Anthro) sources are in red. Source: Ginoux *et al.* (2012).



in North Africa but by agriculture in North America. Taken together these results suggest a high sensitivity of dust emissions to human intervention, which has large implications for climate and biogeochemistry in the future (Mahowald *et al.* 2010).

The most consistent data on the state and trends in the distribution of mineral dust from SDS at the global level comes from satellite data, notably the Total Ozone Mapping Spectrometer (TOMS), but also from measures of aerosol optical thickness (aerosol column concentration) from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) and the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite (see also Section 5). Satellite data is interpreted in conjunction with standard meteorological ground observations to piece together a picture of SDS activity. Data from TOMS have been used to derive an Aerosol Index (AI), which is commonly used as an indicator of the intensity of the dust content (not total dust flux) and is linearly proportional to the aerosol optical thickness (Washington *et al.* 2003). Estimates of dust (or aerosol) optical depth are derived from MODIS Deep Blue data (reflectance bands in the blue region of the electromagnetic spectrum).

Figure 2.9: Integrated 10 year mean (2000–2010) annual dust emission flux in Tg/year for different regions as simulated in present, past, present climate historical land use (pChL), and historical climate present land use (hCpL). Dark green denotes emissions from agricultural source regions and yellow emissions from natural source regions. Note the use of different axis ranges. Source: Stanelle *et al*. (2014).



3. State and Trends of SDS

3.1 Global picture

The largest areas with high aerosol values, which derive from natural and anthropogenic sources, are located in the Northern Hemisphere (Figure 3.1), mainly in a broad "dust belt" that extends from the west coast of North Africa, over the Middle East, Central and South Asia, to China (Prospero *et al.* 2002). There is remarkably little large-scale dust activity outside this region. In particular, the Southern Hemisphere is devoid of major dust activity, although SDS events are important in terms of local impacts. There are smaller concentrations in central Australia, in southern Africa (Bostwana and Namibia), the Atacama in South America, and the North America Great Basin (Figure 3.2). The TOMS data show broad agreement with the global pattern of dust frequency estimated from the synoptic present weather records (Figure 3.3).

In terms of aerosol index (AI) hot spots, the Sahara and the Asian deserts are clearly dominant, whereas AI values are low in the Southern Hemisphere and the Americas (Table 3.1). When the area and AI intensity are combined, the enormity of the Sahara Desert as a dust source becomes evident, a factor of four higher than the Arabia deserts (Goudie and Middleton 2006). Depositional rates associated with some of the major dust trajectories indicate high rates along the Niger River in Mali (Table 3.2):

Most desert dust is emitted from natural sources that experience little human impact (Prospero *et al.* 2002) and the relative contribution of global dust sources that is significantly influenced by human action has large uncertainty, ranging from less than 10% up to 50% of global emissions, but most likely about 25% (see Section 2.4). MODIS Deep Blue data (Figure 3.4) suggest that hydrologic dust sources (e.g., ephemeral

Figure 3.1: Atmospheric Aerosol Eddies NASA Animated Map: 10km GEOS-5 Aerosol Optical Depth (AOD): Red/yellow colours – Dust Aerosols. Source: NASA (2014).

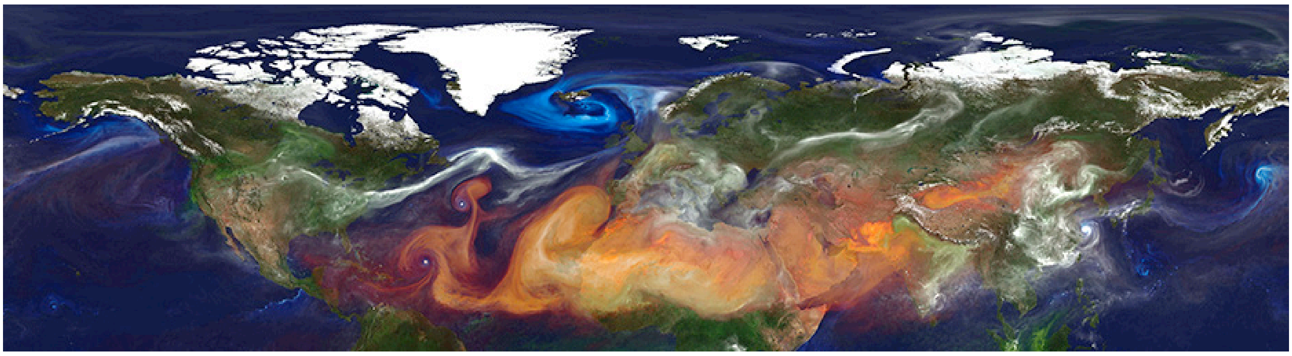


Figure 3.2: The world map of annual mean aerosol index (AI) values (x10) determined by the Total Ozone Mapping Spectrometer (TOMS). Source: Washington *et al.* (2003)

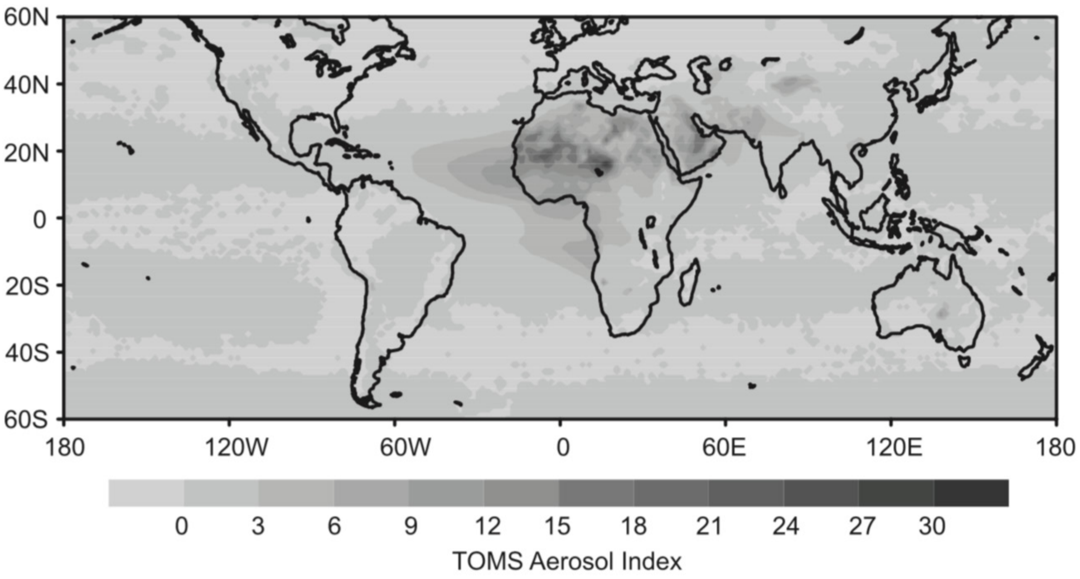
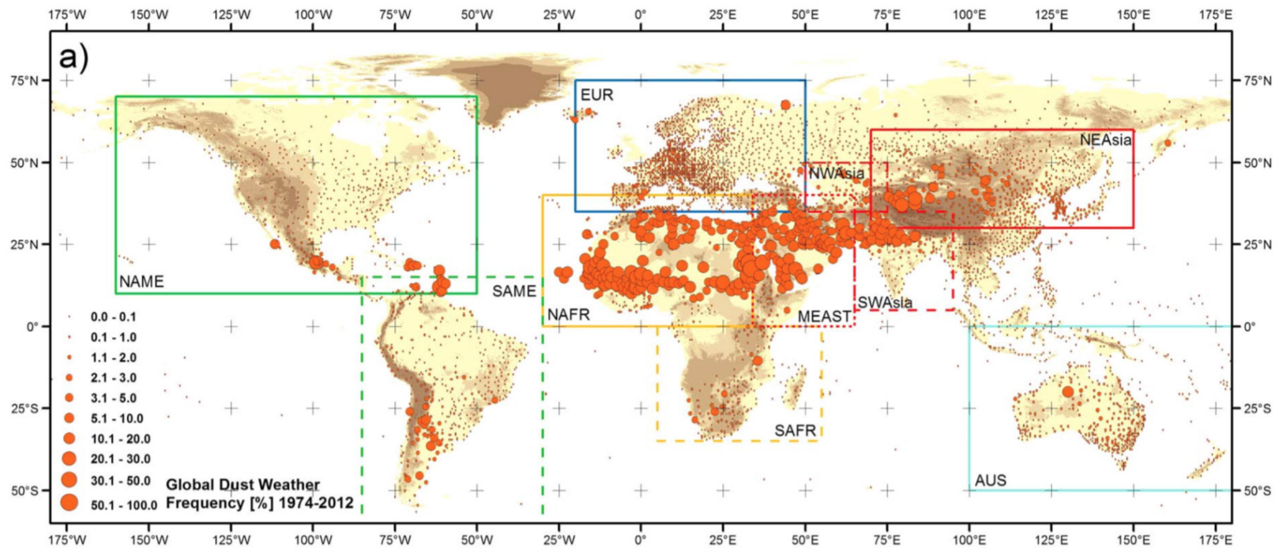


Figure 3.3: Global pattern of dust frequency estimated from the synoptic present weather records for the period of January 1974 to December 2012. Source: Shao *et al.* (2013).



water bodies) account for 31% of emissions worldwide; 15% of them are natural while 85% are anthropogenic (Ginoux *et al.* 2012). About 20% of emissions are from partially vegetated surfaces, primarily desert shrublands and agricultural lands (Ginoux *et al.* 2012).

Most major dust sources are located in arid regions in topographic depressions where deep alluvial deposits have formed by intermittent flooding through the Quaternary and into the Holocene (Prospero *et al.* 2002). In some of these depressions, the layer of alluvium is sufficiently deep to sustain dust emission

Table 3.1: Maximum mean aerosol index (AI) values for major global dust sources determined by data from the Total Ozone Mapping Spectrometer (TOMS). Source: Goudie and Middleton (2006).

Location	AI value	Average annual rainfall (mm)
Bodélé Depression of south central Sahara	>30	17
West Sahara in Mali and Mauritania	>24	5–100
Arabia (Southern Oman/Saudi border)	>21	<100
Eastern Sahara (Libya)	>15	22
Southwest Asia (Makran coast)	>12	98
Taklamakan /Tarim Basin (China)	>11	<25
Etosha Pan (Namibia)	>11	435–530
Lake Eyre Basin (Australia)	>11	150–200
Makgadikgadi Basin (Botswana)	>8	460
Salar de Uyuni (Bolivia)	>7	178
Great Basin of the USA	>5	400

Table 3.2: Depositional rates of dust fallout within some major dust storm trajectories from upwind to downwind. Source: Al-Dousari *et al.* (2013).

Zone-Location	Political region	Reference	t km^{-2} yr^{1}
The western and southern Sahara Desert			
Along Niger River	Mali	McTainsh *et al.* (1997)	913–10,446
Northern Diarnena	Chad	Maley (1982)	142
Kano	Nigeria	McTainsh *et al.* (1982)	137–181
Southern Chad	Chad	Maley (1982)	109
Nouadhibou	Mauritania	Rott (2001)	80
Smara	Western Sahara	Rott (2001)	111

Agadir	Morocco	Rott (2001)	114
Sidi Ifni	Morocco	Rott (2001)	145
Tan Tan	Morocco	Rott (2001)	175
Dakhla	Mauritania	Rott (2001)	191
Boujdour	Western Sahara	Khiri *et al.* (2004)	219
The eastern Sahara Desert			
Libya	Libya	O'Hara *et al.* (2006)	155
Negev Desert	Palestine	Singer *et al.* (2003)	57–217
Crete	Greece	Pye (1992)	10–100
Sudan-Ethiopia, southern Arabia			
Fahal	Oman	Badawy *et al.* (1992)	89
Riyadh	Saudi Arabia	Modaihsh (1997)	392
Northern Arabia			
Dead Sea	Palestine	Singer *et al.* (2003)	45
Baghdad	Iraq	Al-Dabbas *et al.* (2010)	220
Khur Al-Zubir	Iraq	Khalaf *et al.* (1980)	76
Um Qasr	Iraq	Gharib *et al.* (1987)	193
Kuwait	Kuwait	Al-Dousari *et al.* (2013)	270
Gobi and Taklimakan deserts			
Xilingele	Mongolia	Hoffmann *et al.* (2008)	292
Shapotou	China	Li *et al.* (2004)	372
Tokyo	Japan	MOE (1993)	3.5
Australia Desert			
Adelaide	Australia	Tiller *et al.* (1987)	5–10
Namoi valley	Australia	Cattle *et al.* (2002)	17–58

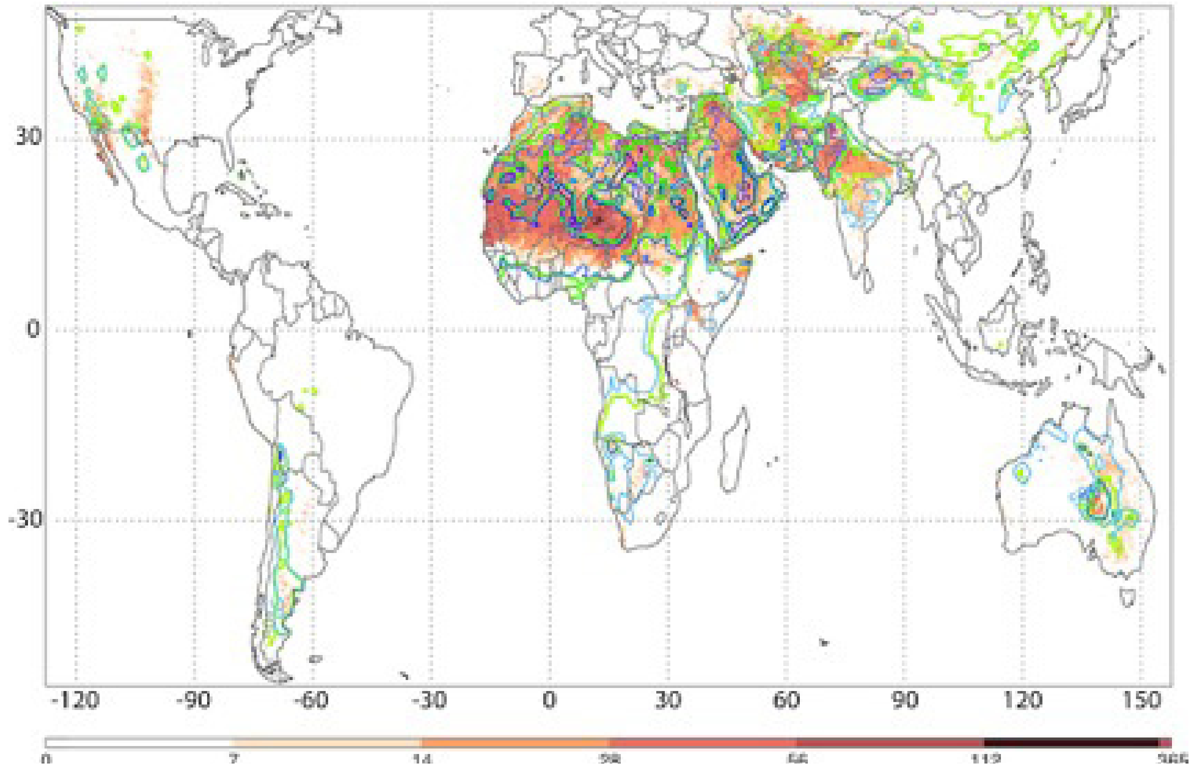
without further replenishing, but others are regularly flooded forming new sediment deposits, which then constitute potential sources. Ephemeral lakes and riverbeds (e.g., wadis) are frequently active dust sources (Ginoux *et al.* 2012).

Many of the major dust sources are adjacent to major sand seas. Although sand particles themselves cannot be transported great distances, they play an important role in the dust generation process through sandblasting (see Section 2.2). Because of the aerodynamic properties of smooth, fine-grained soil surfaces (such as those often found in playas), dust is not readily mobilized unless the soil surface is disrupted (Gillette *et al.*, 1982; Gillette, 1999). The bombardment of the surface by wind-driven sand particles is a highly effective mechanism for grinding and shattering large particles into smaller particles and for ejecting fine particles into the atmosphere. Thus the juxtaposition of playas and fluvial deposits with sand sources may have the effect of enhancing the output of fine dust particles (Prospero *et al.* 2002). Since anthropogenic dust sources are associated with land use and ephemeral water bodies, both in turn linked to the hydrological cycle, their emissions are affected by climate variability, as well as modification of hydrological regimes by human activity.

There is generally a strong correlation between SDS and amount of annual rainfall, with many of the largest dust source regions occurring in hyperarid areas (Table 3.1). Outside hyperarid areas, the association between drought phases and enhanced SDS is well established, though there are different time lags in different regions (Zender and Kwon 2005), with a very direct relationship between drought spells and annual dust storm frequency in Australia (McTainsh *et al.* 2005) and the Sahel (Middleton 1985; Street-Perrott *et al.* 2000).

The seasonal timing of SDS is related to various factors, including rainfall patterns, snow cover, hydrology of closed lake basins, wind energy, convectional activity, weather fronts, and agronomic activities (Goudie and Middleton 2006). SDS tend to occur most frequently in many regions during the afternoon due to various factors related to wind speed, soil drying, turbulence and pressure gradients due to surface heating by the sun, and breakdown of nocturnal temperature gradients during the day

Figure 3.4: Annual mean frequency distribution of dust storms using four indicators: MODIS Deep Blue Level 2 (2003–2009), Dust Optical Depth > 0.2 (red), TOMS (1980– 1991) aerosol index ≥ 0.5 (blue), and Ozone Mapping Instrument (OMI) (2004–2006) aerosol index ≥ 0.5 (green). The isocontours of TOMS and OMI have been removed over oceans for clarity. Source: Ginoux *et al.* (2012).



(Littmann 1991; Goudie and Middleton 2006). The duration of SDS is typically only a few hours, but can last for up to several days (Goudie and Middleton 2006).

3.2 Regional picture

The account below of regional state and trends in sand and dust storms is largely based on the analysis by Ginoux *et al.* (2012) based on MODIS Deep Blue estimates of dust optical depth in conjunction with other data sets on land use for the period 2003 to 2009. These authors found the distributions of the most active dust sources compared well with the distributions derived from previous studies using the Nimbus 7 TOMS Aerosol Index from 1978 to 1991 (Prospero *et al.* 2002) and with the more recent OMI aerosol index, which covers 2003 to 2006.

Comparing all three data sets, there appear to have been no major changes in dust activity over the past three decades over North Africa, the Middle East and South America, whereas there have been substantial changes in the US high plains, central Asia and Australia (Ginoux *et al.* 2012).

3.2.1 The Sahara, Northern Africa and Southern Europe

The Sahara is the most significant global source of dust, accounting for half of all aeolian desert material supplied to the world's oceans (Goudie and Middleton 2006). Recent analyses (Figure 3.5) show the southern Sahel sources are overwhelmingly anthropogenic (locations 1 to 5), whereas the Sahara is the most significant natural source (locations 6 to 11). This could be explained by the fact that agricultural and grazing activities in regions with annual rainfall of 200 – 250 mm are confined to relatively localized areas around point sources of water, and most agricultural and grazing activity takes place in wetter areas south of the 200 – 250 mm isohyets (Prospero *et al.* 2002). The sources in the Atlas Mountains (locations 20 to 23) and along the Mediterranean coast (e.g., location 19) are also mostly anthropogenic.

The Sahel dust emissions are related to land use. Measurements in the 1950s (Gill 1996) showed that playas and ephemeral lakes were reactivated by overgrazing and cultivation in Senegal (location 1), as well as from Lake Faguibine in Mali (blue spot in location 3 at the border with Mauritania). Analysis of thousands of years of dust deposition in the mouth of the Senegal River showed a sharp increase in deposition after the advent of commercial agriculture in the Sahel, about 200 years ago (Mulitza *et al.* 2010). Dust storms originating from alluvial sediments of the Inland Delta of the Niger River (location 3), near Mopti in Mali, have been associated with disturbance by livestock of surface crusts (Nickling and Gillies 1993).

The Senegal River Basin (location 1) has dust events for up to 60% of days per year. Analysis of 50 years of visibility data and aerial photos along the Senegal River suggests that land degradation (gully erosion, riverbank erosion) following deforestation, and drought years during 1954 to 1992, appear to have led to increased wind erosion and dust production (Niang *et al.* 2008). Increased offshore sediment deposition has also been shown to coincide with the onset of agriculture in the region (Mulitza *et al.* 2010). The pattern of deforestation followed by water and wind erosion could be expected to have also occurred in the Niger River and would suggest that sources in the Sahel are largely controlled by river stream-flow and soil disturbance (Ginoux *et al.* 2012).

Outside the Sahel, the major sources are natural (Prospero *et al.* 2002; Figure 3.5). These include major depressions (Bodélé, location 7, and Qattarah, location 17), large basins with sand seas (Erg of Bilma, location 8; Erg el Djouf, location 10; Grand Erg Occidental, location 13; Grand Erg Oriental, location 14; and Libyan Desert, location 15), ephemeral lakes (Sebkhet te-n-Dgâmcha, location 11; Chott el Jerïd, location 19; Chott Melrhir, location 20; and lakes in the Tiris Zemmour region, location 12), and the Nile River Basin (location 16).

The Bodélé depression (location 7) is by orders of magnitude the largest dust source in the world (Prospero *et al.* 2002) and has been related to an effect of the Harmattan winds passing between the Ennedi (location C) and Tibesti (location D) mountains (Washington *et al.* 2006). Additional sources (location 5) are associated with alluvial fans and wadis on the flanks of the Ennedi (location C) and Ouaddai highlands (location B). Alluvial sediments (location 9) are also sources on the southern flank of the Aïr and the Ahaggar (location E) mountains.

Dust activity is also seen along the Mediterranean basin in Andalusia (location 24) and Cyprus (location 18), especially in summer, with maximum activity over the fluvial plains of the Guadalquivir and Segura Rivers in southern Spain. The Konya plain is a hot spot of wind erosion in Turkey (Avci 2011). Agriculture is the main cause of these sources (Fernandez *et al.* 2000). Desertification in the western Mediterranean basin has been triggered by climatic variability and demographic disequilibrium and the associated changes in agricultural practice (Puigdefábregas and Mendizabal 1998; Zdruli, 2014).

Saharan dust is regularly transported along four main transport paths (Goudie and Middleton 2006). There is southwestward transport to the Gulf of Guinea, the Ivory Coast and Ghana. A westward path takes dust over the North Atlantic to the Canary Islands, North America and South America. A northward route transports dust across the Mediterranean to southern Europe and even to Scandinavia and the Baltic. An eastward path takes dust across the Mediterranean to the Middle East and as far as the Himalayas, East Asia and Japan. The westward dust movement is the largest flow, accounting for 30 – 50% of the output, with the longer-lived plumes transporting dust the furthest. For example, transport to the Caribbean, where 20 million tonnes of Saharan dust are deposited annually, typically takes 5 to 7 days. About 80 to 120 million tonnes per year are transported to Europe and mostly deposit with precipitation. Eastern Mediterranean deposition is primarily from North Africa.

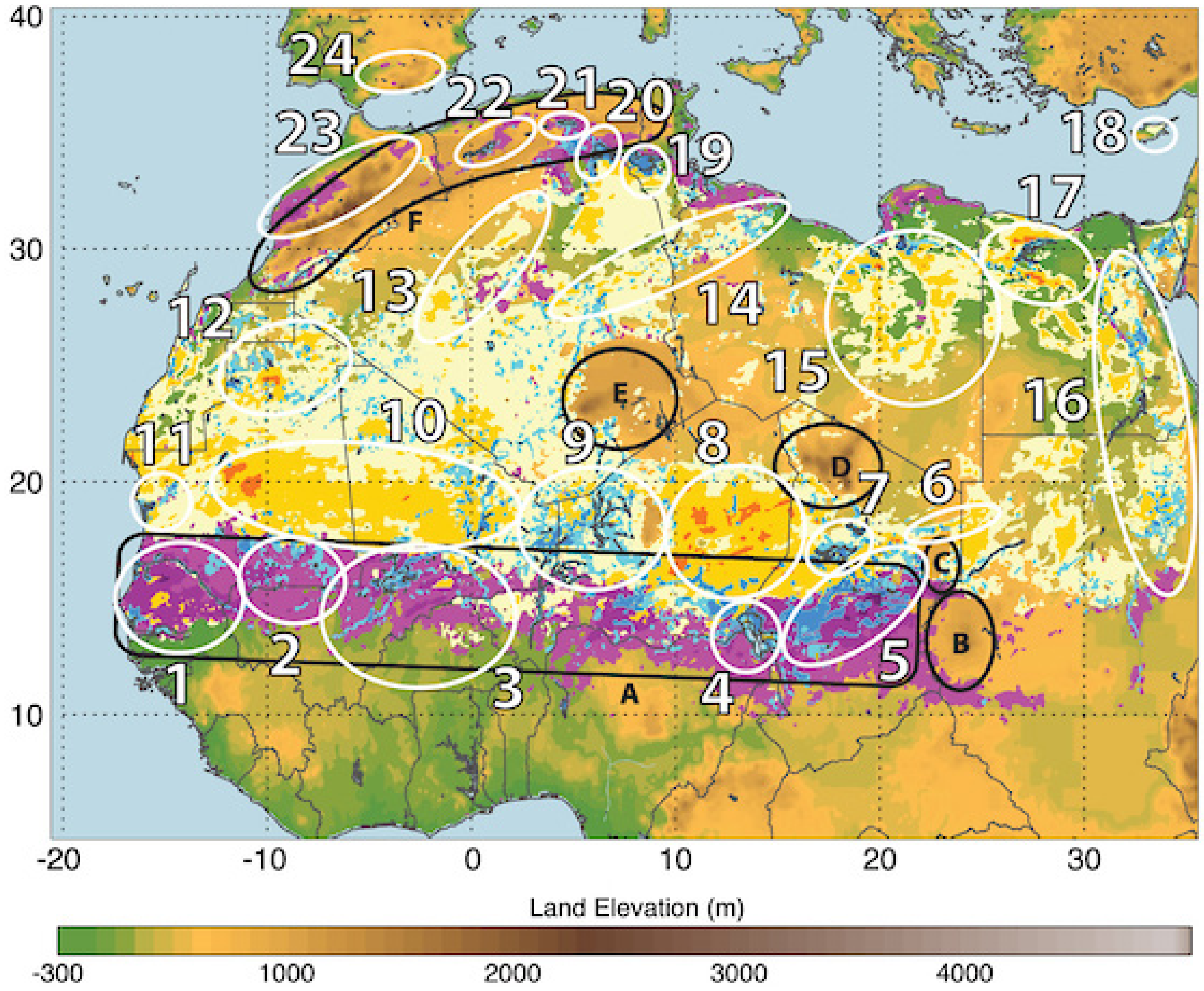
Increases in dust event frequency and duration in the Sahel, have been observed since the late 1950s, concurrent with drought periods (Middleton 1985; Goudie and Middleton 1992; N'Tchayi *et al.* 1997) and are possibly indicative of climate change. The deflational power of the wind also seems to have increased between 1970 and 1985 (Clark *et al.* 2004). The trends are corroborated by data showing increases in Saharan dust deposition in many depositional areas in Europe and Barbados (Goudie and Middleton 2012).

A dramatic downward trend in North African dustiness and transport to the tropical Atlantic Ocean since the 1980s has been observed by different data sets and methods. This has been attributed to recovery of vegetation cover as a result of rainfall increases following the droughts of the 1980s, resulting in greater surface roughness, leading to reduced surface wind (Cowie *et al.* 2013). However, another study (Ridley *et al.* 2014) concluded that the reduced surface winds over dust source regions in Africa were not directly linked with changes in land use or vegetation cover.

3.2.2 Middle East and East Africa

The Middle East shows a complex mixture of natural and anthropogenic sources (Figure 3.6; Mesopotamia (location 11) has a frequency of occurrence of Dust

Figure 3.5: Distribution of the percentage number of days per year with Dust Optical Depth > 0.2 over West and North Africa and Southern Europe. The frequencies associated with hydrologic sources are shaded in blue, with natural land use in yellow to red, and anthropogenic land use (more than 30%) in magneta. The frequency levels are 10%, 20%, 40%, 60%, and 100%. Topography shading varies from dark green (300 m) to brown (1000–4000 m), then to grey for high elevation up to 8000 m. The white circled source areas are numbered as follows: 1, Senegal River Basin; 2, Aoukar depression; 3, upper Niger River Basin; 4, Lake Chad; 5,river drainage basin of the Ennedi and Ouaddaï highlands; 6, Mourdi depression; 7, Bodélé depression; 8, Grand Erg of Bilma; 9, river drainage basin of the Aïir; 10, Erg El Djouf; 11, Sebkhet te-n-Dgâmcha; 12, Tiris Zemmour region; 13, Grand Erg Occidental; 14, Grand Erg Oriental; 15, Libyan Desert; 16, Nile River Basin; 17, Qattarah depression; 18, Mesaoria plain in Cyprus; 19, Chott el Jerïd; 20, Chott Melrhir; 21, Chott el Hodma; 22, Chott ech Chergui; 23, Morocco coastal plains; and 24, Andalusia in Spain. Some geographic features are contoured in black and are labeled as follows: A, the Sahel; B, the Ouaddaï Highlands; C, Ennedi; D, Tibesti; E, Ahaggar; and F, Atlas Mountains. Source: Ginoux *et al.* (2012).



Optical Depth >0.2 of more than 20% over most of the area. The region was described as a major source of dust since the 1980s (Middleton 1986b). The dust from the region between the Tigris and Euphrates is mapped as natural in Iraq (although upstream water control is an issue) and anthropogenic in Syria. The maximum frequency (>60%) is located over the farmland region northeast of the city of Ar Raqqah (Syria) in the northwestern part of the region (location 11). There is an extensive area of anthropogenic sources, mixed with hydrologic sources, in Saudi Arabia (location 9) essentially aggregated around wadis (dry riverbed).

In the United Arab Emirates, the Rub' al Khali sandy desert (location 8), notably in the Sabkha Matti, which extends from the Emirates into Saudi Arabia, sand dunes provide a source of sand that sandblasts the surface to generate dust storms. Sand storms are reportedly becoming an environmental problem in the area (Abdelfattah 2009).

There is a cluster of anthropogenic and hydrologic sources along the Jordan River, particularly on the east side (location 10), which corresponds to the Wadi Araba Desert. Diversion of water from the Jordan River has induced wind erosion of desiccated sediments (Gill 1996). In Yemen, large dust sources are associated with river fans at the base of the coastal escarpment in the Hadramawt (location 7).

Iran has a prominent source along its west coast (location 13), the northwestern part of which is anthropogenic. The other major sources in Iran are associated with large salty lakes, such as the southern shore of the Urumia Lake (location 12), or in the Hamun-i-Mashkel (location 14) and the Dasht-e Kavir (location 16) Deserts. Land use change and desiccation of lakes in the Hamun-i-Mashkel has increased the frequency and severity of dust storms (Rashki *et al.* 2012). Because of water diversions, Urumia Lake is becoming a new source of salt dust (Zarghami 2011) much like the Aral Sea today.

The plains between the Caspian and Aral Seas are largely irrigated for agriculture and provide active anthropogenic dust sources. Specific sources are the delta of the Atrek River (location 18) and the Turan plain (location 19). The dramatic decrease in the size of the Caspian Sea, because of water diversions, has led to rapid exposures of formerly inundated land (Dickerson 2000), which has now become a dust productive region.

The diversion of river water for irrigation has greatly reduced river flow and is the fundamental cause of the desiccation of the Aral Sea (Micklin 2010). The Aral Sea was formerly one of the largest lakes in the world (area 68,000 km^2) but is now reduced to 10% of its original size. Large areas of the Aral Sea are now active dust sources (location 20), in agreement with in situ measurements (Wiggs *et al.* 2003). Desiccation of lakes and soil surfaces by inter-basin water transfers and groundwater depletion is also a risk (e.g., the Caspian Sea and the Tigris-Euphrates Basin).

Although much dust in the Middle East derives from local sources, substantial amounts of dust come from the Sahara. For example, in March 2002, a large dust storm from north eastern Africa reached Iran (Goudie and Middleton 2006). An example of dust storm trajectories in the Persian Gulf is shown in Figure 3.7.

In northeast Africa (Figure 3.6), the dust sources are associated with arid or semiarid areas: the Chalbi Desert and semiarid northeastern province of Kenya (location 1), the coastal desert of Somalia (location 2), the arid Nogal Valley (location 3), the Danakil Desert in the Dafar Depression of Ethiopia (location 4), Lake Tana of Ethiopia (location 5), and the coastal region of northeast Sudan (location 6). The Chalbi and Danakil Deserts were paleolakes but with changing climate became dust sources (Nyamweru and Bowman 1989). The Somalia coastal and Nogal Lake sources appear to be predominantly anthropogenic sources.

Figure 3.6: Distribution of the percentage number of days per season (March, April, and May) with Dust Optical Depth > 0.2 over Eastern Africa and the Middle East. The colour shadings are the same as in Figure 3.5. The white circled source areas are numbered as follows: 1, Chalbi Desert of Kenya; 2, coastal desert of Somalia; 3, Nogal Valley of Somalia; 4, Danakil Desert of Ethiopia; 5, Lake Tana of Ethiopia; 6, northeast Sudan; 7, Hadramawt region; 8, Empty Quarter; 9, highlands of Saudi Arabia; 10, Jordan River Basin of Jordan; 11, Mesopotamia; 12, Urumia Lake of Iran; 13, coastal desert of Iran; 14, Hamun-i-Mashkel; 15, Dasht-e Lut Desert of Iran; 16, Dasht-e Kavir Desert of Iran; 17, Qobustan in Azerbaijan; 18, Atrek delta of Turkmenistan; 19, Turan plain of Uzbekistan; and 20, Aral Sea. Source: Ginoux *et al.* (2012).

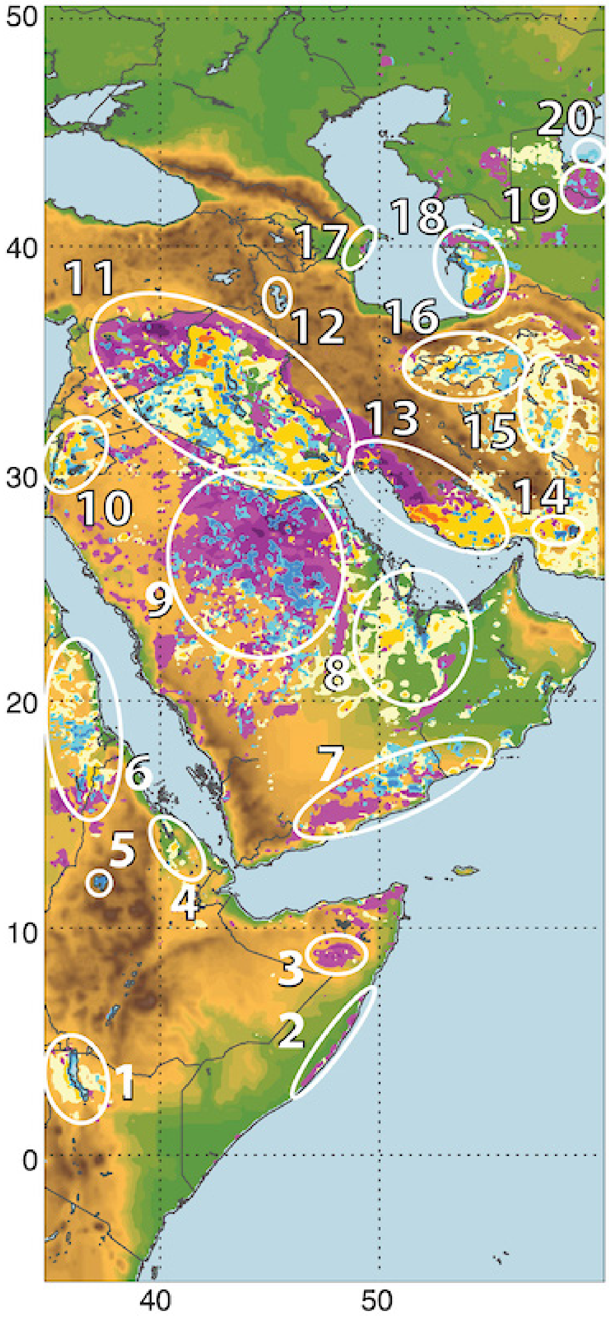
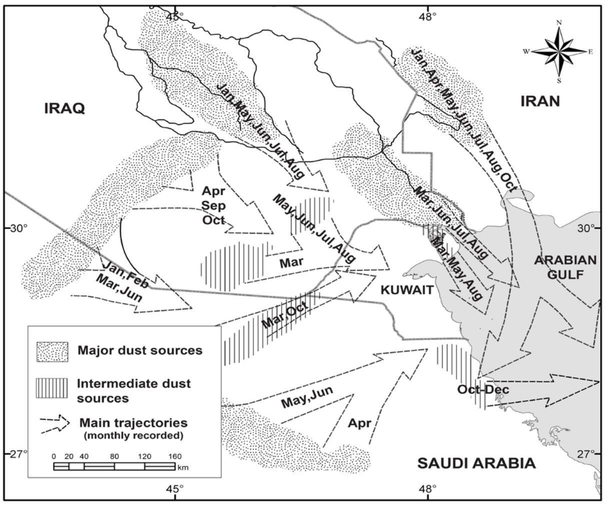


Figure 3.7: Major and intermediate source areas and trajectories for dust storms in the north-western areas of Persian Gulf based on dust storm days in Kuwait and satellite images from 2000 to 2010. Source: Al-Dousari and Al-Awadhi (2012).



3.2.3 Southern Africa

Southern Africa possess two of the three largest dust sources in the southern hemisphere: Etosha and Makagadikgadi (Table 2.5; Figure 3.8). The distribution of activity varies seasonally except for the Namib Desert (location 1), which is active during most seasons. Dust plumes have been observed streaming from the Kalahari and Namib across the South Atlantic (Eckardt *et al.* 2002). Dust events in Southern Africa are mostly associated with enhancement of the low-level easterly circulation over the interior of the region (Eckardt *et al.* 2002).

Sources along the eastern margin of the escarpment bordering the Namib Desert, especially from December to February, are associated with silt deposits (locations 1 and 12). There are extensive sources (Soderberg and Compton 2007) associated with the Kalahari Desert (location 10), including the Makgadikgadi Pans (location 9), which are influenced by the extent and frequency of lake inundation, sediment inflows, and surface wind speed variability (Ginoux *et al.* 2012). Other sources include the area along the southwest coast associated with the Namaqualand Desert (between location 1 and 2), crop lands near Capetown (location 2), and the Highveld region around the Bloemhof Dam (location 4). There are also active dust sources in Zimbabwe (Hippo Valley, location 5) and Mozambique (Cahora Bassa reservoir, location 8) during September to November.

Areas that are covered by savanna woodland and grassland, for example in northern Botswana and northern Namibia, appear to be protected from deflation (Goudie and Middleton 2006). Wind erosion has been associated with the semiarid southwest of Madagascar (location 6) by Feddema (1998), and there are active dust sources before the rainy season in parts of northern Madagascar (location 7).

A dust inventory, using visually interpreted MODIS and Meteosat Second Generation (MSG) thermal infrared composite (MSG-SEVIRI) data, provides more detail (Figure 3.9) and further demonstrates the major sources and their seasonality (Vickery *et al.* 2013). The study identified the main sources as ephemeral inland lakes, coastal pans as well as dry river valleys in Namibia, Botswana, and South Africa.

Figure 3.8: Distribution of the percentage number of days per season (a: September, October, and November; and b: December, January, and February) with Dust Optical Depth > 0.2 over Southern Africa. The colour shadings are the same as in Figure 3.5. The white circled source areas are numbered as follows: 1, Namib Desert; 2, croplands near Cape Town in South Africa; 3, South African Bushmanland; 4, Bloemhof Dam of South Africa; 5, Hippo Valley of Zimbabwe; 6, southern Madagascar; 7, northern Madagascar; 8, Cahora Bassa reservoir of Mozambique; 9, Makgadikgadi Pans of Botswana; 10, Kalahari Desert; 11, Etosha Pan; and 12, Great Escarpment of Namibia. Source: Ginoux *et al.* (2012).

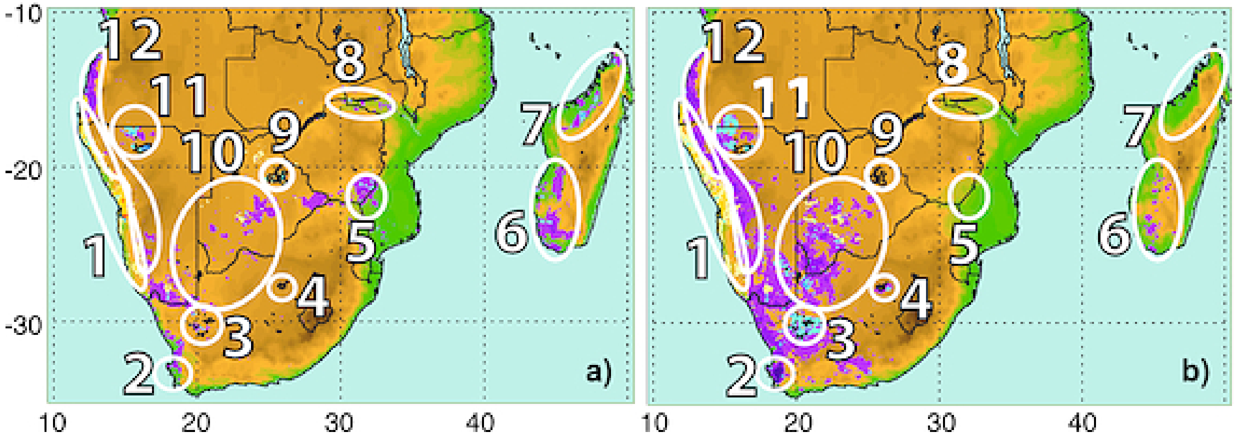
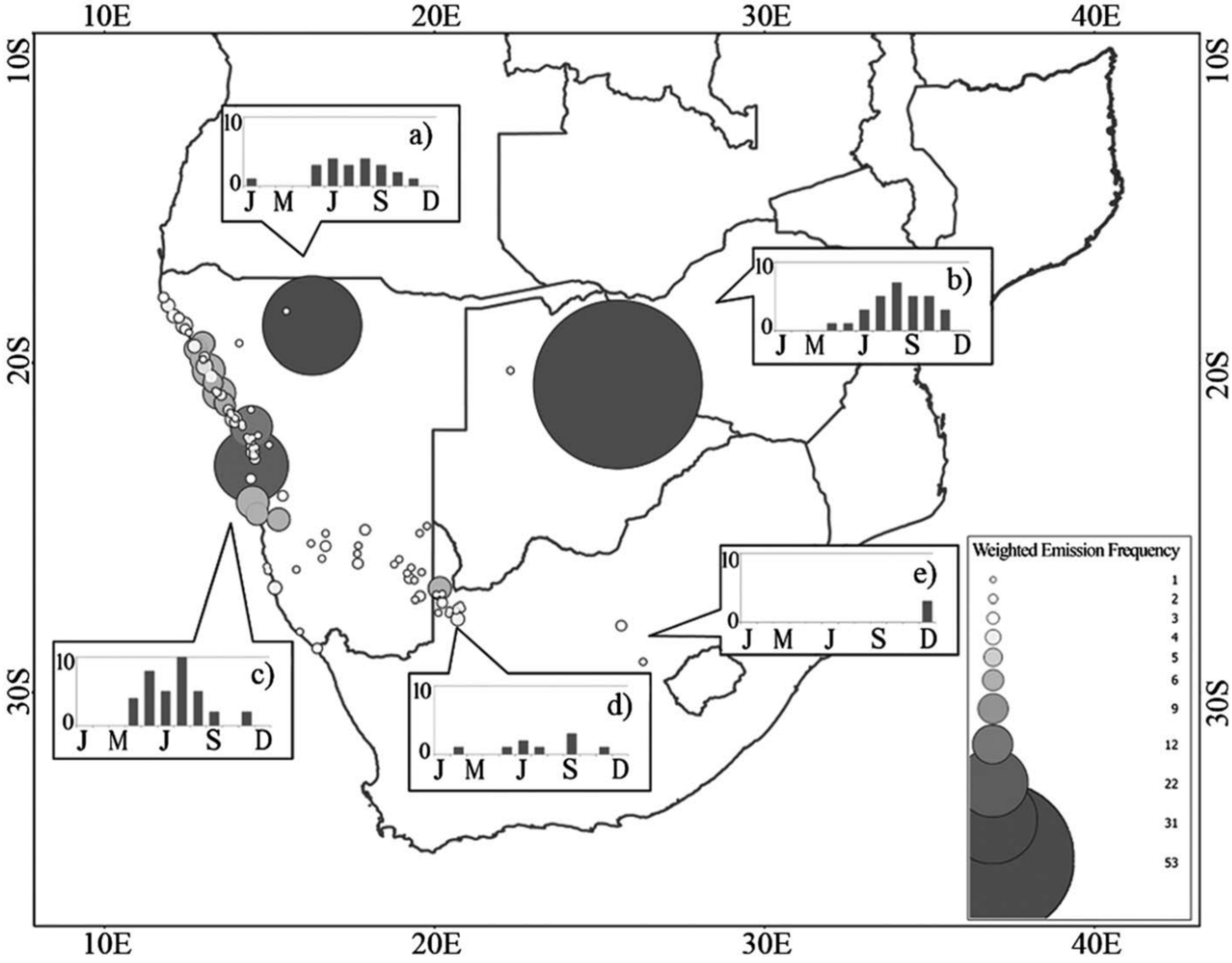


Figure 3.9: Southern African dust plume source locations. Plume frequency and timing for the various regions: (a) Etosha Basin, (b) Makgadikgadi Basin, (c) Namib Coastal Sources, (d) South Western Kalahari Sources, (e) Free State Sources. Circles indicate the weighted frequency of the number of dust plumes, clearly indicating the dominance of the Makgadikgadi and Etosha Pans in detected plume frequency. The bar charts represent the number of days on which each region had detected dust plumes. Source: Vickery *et al*. (2013).



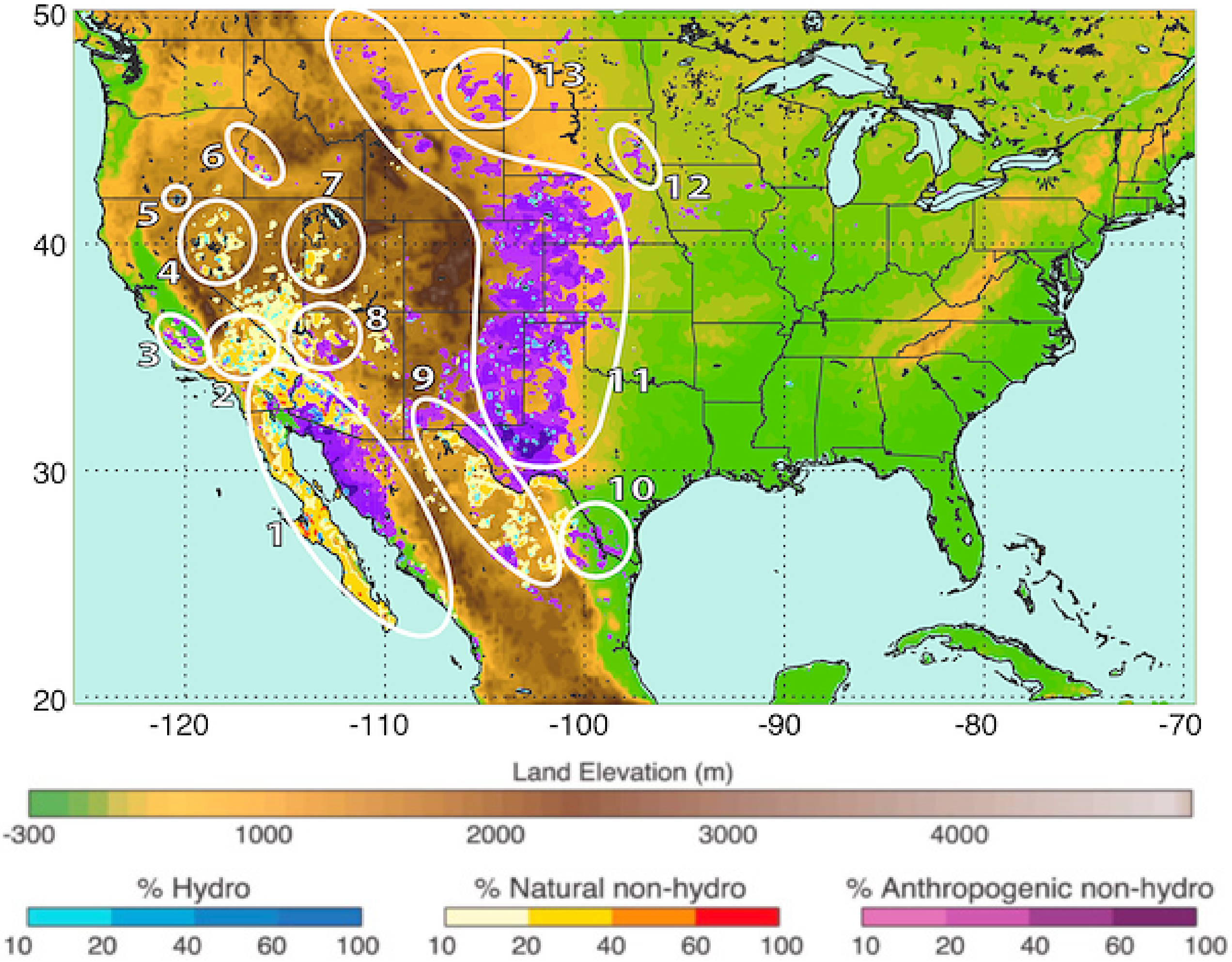
3.2.4 North America

The greatest dust activity in North America (Figure 3.10) occurs in the high plains (location 11), extending from Montana to southern Texas, and is primarily anthropogenic except for a few ephemeral lakes. This semiarid and subhumid region accounts for 60% of wind erosion in the US, with the highest frequency located in the southern plains of Texas, which experience 50 dust days per year, the USA national maximum (Hagen and Woodruff 1973). There is a significant anthropogenic source in the east of the Sonoran Desert (location 1), along the east coast of the Gulf of California in Mexico, which supports irrigated agriculture. Major river basins appear as potential dust sources, although relatively weak, and correspond with locations of cropland that have the greatest potential for wind erosion (Nordstrom and Hotta 2004).

There are many natural or anthropogenic sources related to ephemeral water bodies. For example, Owens Lake in California (location 2) was desiccated by water diversions of the Owens River into Los Angeles Aqueduct since 1913 (Gill 1996). The desiccation of Goose Lake, among others, has led to blowing plumes of salt dust (Gill 1996). Other such sources include the Great Salt Lake Desert (location 7), the Mojave Desert (location 2), and the Sonoran Desert (location 1). Other natural sources include Black Rock and Smoke Creek Deserts (location 4), the Great Salt Lake Desert (location 7), Mojave Desert (location 2), and Chihuahuan Desert (location 9).

Although the dust bowl of the 1930s is most widely known (see Section 2.4), dust storms are still a serious problem in the USA. For example, in the San Joaquin Valley of California in 1977, a combination of drought and high winds caused extensive soil erosion and

Figure 3.10: Distribution of the percentage number of days per season (March, April, and May) with Dust Optical Depth > 0.2 over North America. The colour shadings are the same as in Figure 3.5. Some source areas are contoured in white and are numbered as follows: 1, Sonoran Desert; 2, Mojave Desert; 3, San Joaquin Valley; 3, Black Rock-Smoke Creek deserts; 4, Goose Lake; 6, Snake River; 7, Great Salt Lake Desert; 8, Colorado River; 9, Chihuahuan Desert; 10, Rio Grande; 11, High Plains; 12, Big Sioux River; and 13, lower Yellowstone Valley. Source: Ginoux *et al.* (2012).



damage over an area of 2,000 km², with more than 25 million tonnes of topsoil lost from grazing land within a 24-hour period (Goudie and Middleton 2006). Dust storms leading to topsoil loss also occur in the Canadian Prairies, especially in the spring when vegetative cover and precipitation are low (Wheaton 1992).

There has been an increase in calcium deposition over the past 17 years in the inter-mountain west, the midwest, and the northwest of the USA attributed to mineral aerosol emissions, which ties with independent evidence showing increases in the frequency of dust storms and low-visibility days across regions of the western US (Brahney *et al.* 2013). This analysis indicated that the trend of increased mineral aerosol emissions is most likely due to an interaction between wind speeds, drought cycles, and potentially changes in human land uses. Increased drought frequency and greater soil aridity have the potential to increase dust emissions in the future, which can further contribute to regional aridity (Cook *et al.* 2009).

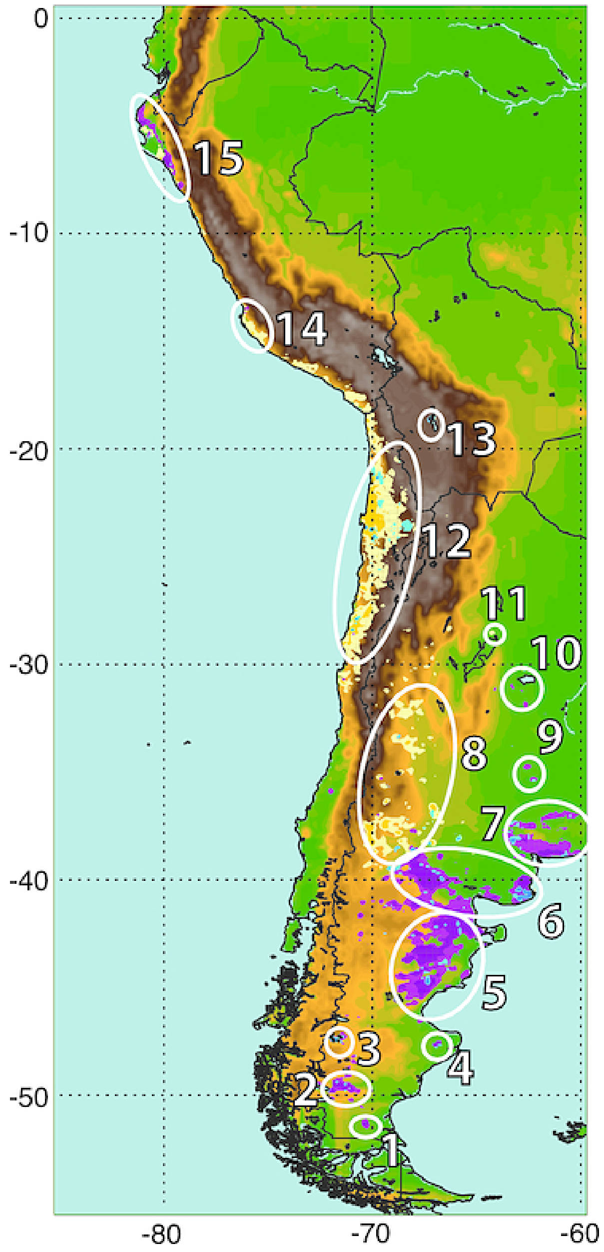
3.2.5 South America

The largest natural sources of dust in South America (Figure 3.11) are located in the Atacama Desert of Chile (location 12), followed by the Nazca (location 14) and Sechura (location 15) deserts of Peru, and are natural non-hydrologic sources. Other natural sources of dust in Argentina are associated with salt lakes (locations 9, 10 and 11). Most dust activity occurs in the winter months (December – February).

The main anthropogenic sources (locations 5 and 6) are in the Argentine Pantagonia, often associated with major river basins. The tract to the west of Buenos

Aires experiences more than eight dust storms per year (Middleton 1986a; Box 3.1). Sheep ranching is largely responsible for the desertification of Patagonia and is the cause of the observed doubling of dust in Antarctic Peninsula ice cores during the twentieth century (McConnell *et al.* 2007). Riparian areas and wetlands are heavily impacted by grazing due to concentration of livestock around water sources. In addition to direct disturbance of soil cover, indirect effects of climate change may play a role.

Figure 3.11: Distribution of the percentage number of days per season (December, January, and February) with Dust Optical Depth > 0.2 over South America. The colour shadings are the same as in Figure 3.5. The white circled source areas are numbered as follows: 1, Gallegos River; 2, San Martin and Viedna lakes; 3, Lake Pueyrredon; 4, ephemeral lakes in the Deseado district of Santa Cruz Province; 5, coastal plains of Chubut Province; 6, Rio Negro plain; 7, Buenos Aires Province; 8, eastern flank of the Andes; 9, Laguna Salada; 10, Laguna Mar Chiquita; 11, Salinas Grandes Desert in Argentina; 12, Atacama Desert of Chile; 13, Lake Poopo of Bolivia; 14, Nazca Desert of Peru; and 15 Sechura Desert of Peru. Source: Ginoux *et al.* (2012).



3.2.6 South Asia

The northern part of the Indian sub-continent (Figure 3.12) is a major dust source, largely associated with ephemeral water bodies ranging in scale from the major rivers to small lakes, and driven by land use. Dust activity in the region is highly seasonal due to the seasonality of rainfall (monsoons), which determine vegetation cover and soil moisture, and the occurrence of thunderstorms prior to the onset of the monsoons (Goudie and Middleton 2006). The Indo-Gangetic basin (locations 1, 2, and 3) is a principal source, characterized by intense agricultural activities as well as persistence of dust transported from desert regions of western India (Prasad *et al.* 2007). The highest SDS frequency is observed in the Rajasthan province (location 2) with observed frequency exceeding 70% along the seasonal Ghaggar River. Human-influenced desertification processes have resulted in wind erosion and deposition of sediments in saline lake basins in Rajasthan (Gill 1996) and agricultural areas in the Indian Plateau. The Rajasthan Desert is a significant dust source of southwest Asia (Pandithurai *et al.* 2008). Some seasonal lakes are also extensive (e.g., Rann of Kutch, location 8).

In Pakistan, the observed frequency of dust storms exceeds 40% in the Lakki Marwat district over the fluvial plain of the Karram River, a tributary of the Indus (location 3). These are mostly natural non-hydrologic sources, with more than 70% frequency in the fluvial plain of the Dasht River near the border with Iran. Ground observations indicate that the highest frequency of dust storms occurs at the convergence of the borders of Iran, Pakistan and Afghanistan (Middleton 1986b). For example, the bed of Lake Hamun and the large deltaic fan of the Helmand River are well documented sources of dust storms, probably caused by diversion of upstream water for irrigation use and by extreme droughts in recent years (Goudie and Midleton 2010). The Makran coast (location 7), a hyper-arid area, is one of the major global dust sources (Goudie and Middleton 2001), derived from near-shore sediments.

In Afghanistan, there is an extensive anthropogenic source in the Hindu Kush (location 4), with many rivers feeding into the Helmand River supporting irrigated agriculture. There is a natural source from seasonal lakes within the Sistan Basin (location 5), extending into Iran.

Box 3.1: The Argentinian dust bowl in the southwest of Buenos Aires

The Southwest of Buenos Aires Province (SW-BAP) in Argentina is a classic example of how desertification processes can occur and result in dust storms. The affected region, which covers 6.5 million hectares, includes 7,825 farms (in 2002) and supports 550,000 people. Farming activities include irrigated crop lands and rainfed, mixed production systems (beef cattle and wheat). Mean annual rainfall for 1940-2014 was 407 mm, with rainfall below the mean in 60% of the years.

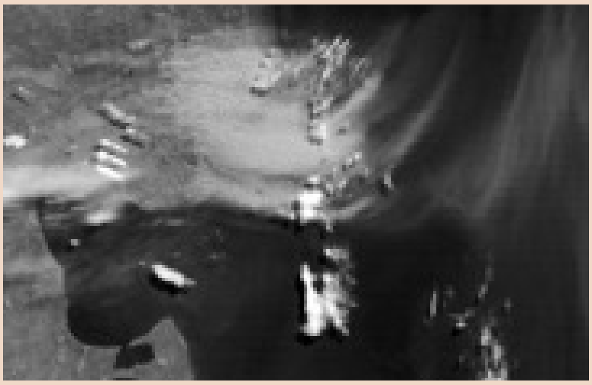
SW-BAP is one of the areas in South America most affected by wind erosion (Bouza *et al.* 2012). It is susceptible to desertification due to the combination of land mismanagement and recurrent droughts. During wet cycles, producers increase both stocking rate and the area sown to wheat, using the same farming practices as used in the humid Pampas. However, during dry cycles, land is abandoned and fields become covered by sand and invasive plants.

Bouza *et al.* (2012) measured wind erosion in a smooth field with no vegetation cover during the April-November 2009 at Southern National University, Bahía Blanca. Rainfall was 143 mm over this period, only 21% of the historical average (1991-2000). The study indicated a strongly negative water balance and an edaphic condition favourable for deflation due to scarce moisture. Mean wind speed, measured at 2 m above ground level for 14 recorded storms, was 32.5 km h^{-1} (range 25.9 to 40.6 km h^{-1}). In about 70% of the cases, the prevailing wind direction was NNW. Soil loss for the entire sampled period was 56.8 t ha^{-1}. Other studies in the southwest of Buenos Aires Province (Silenzi *et al.* 2011) have indicated that the loss of a centimetre of soil produces an average reduction in wheat yield of about 50 kg ha^{-1}. These studies reported that, out of the 3.16 million ha that are used for wheat cropping, 639,720 ha has had a historical loss of about 10 cm of soil. As a consequence, the annual reduction in the wheat yield was estimated at about 320,000 tons, equivalent to USD 58 million (using 2016 wheat prices).

Damage from wind erosion is not limited to agriculture. Blowing soils affect the 928 km National Road Nº 3, particularly along a 15 km stretch of the road at La Querencia. It is common for motor traffic to be stopped because of visibility problems and sand encroachment on the road. More than 0.20 m of soil have eroded and sand has accumulated along the barrier fences in this area. Dried clumps of Salsola kali (a thistle) are blown from the fields and become trapped in the fences. The characteristic landform consists of mounds, dunes and nebkas (sand mounds around shrubs or trees), which can reach dimensions of up to several meters. The blowing soil also uncovers the bare rock or plough pans, leading to the formation of desert pavement. The dust generated often reaches Bahia Blanca city and sometimes travels 400 km into the Atlantic Ocean

The SW-BAP phenomenon, which begin in the 1930s and 1950s, has been compared with the USA Dust Bowl of the 1930s. Similar impacts are being felt in terms of impoverishment of producers, loss of productive soils, and damage to infrastructure and urban areas. The SW-BAP has become an important source of dust emissions, comparable to other internationally well-known sources such as the Sahara, especially the Bodélé Depression, the drylands of Mauritania, Mali and Algeria in the Sahel (Middleton and Goudie 2001), and the dry environments of China, Arabian Peninsula, Iran, Pakistan, and India (Wang 2015; Zhang *et al.* 2003).

Dust bowl affecting road infrastructure and vehicle transit in "La Querencia".



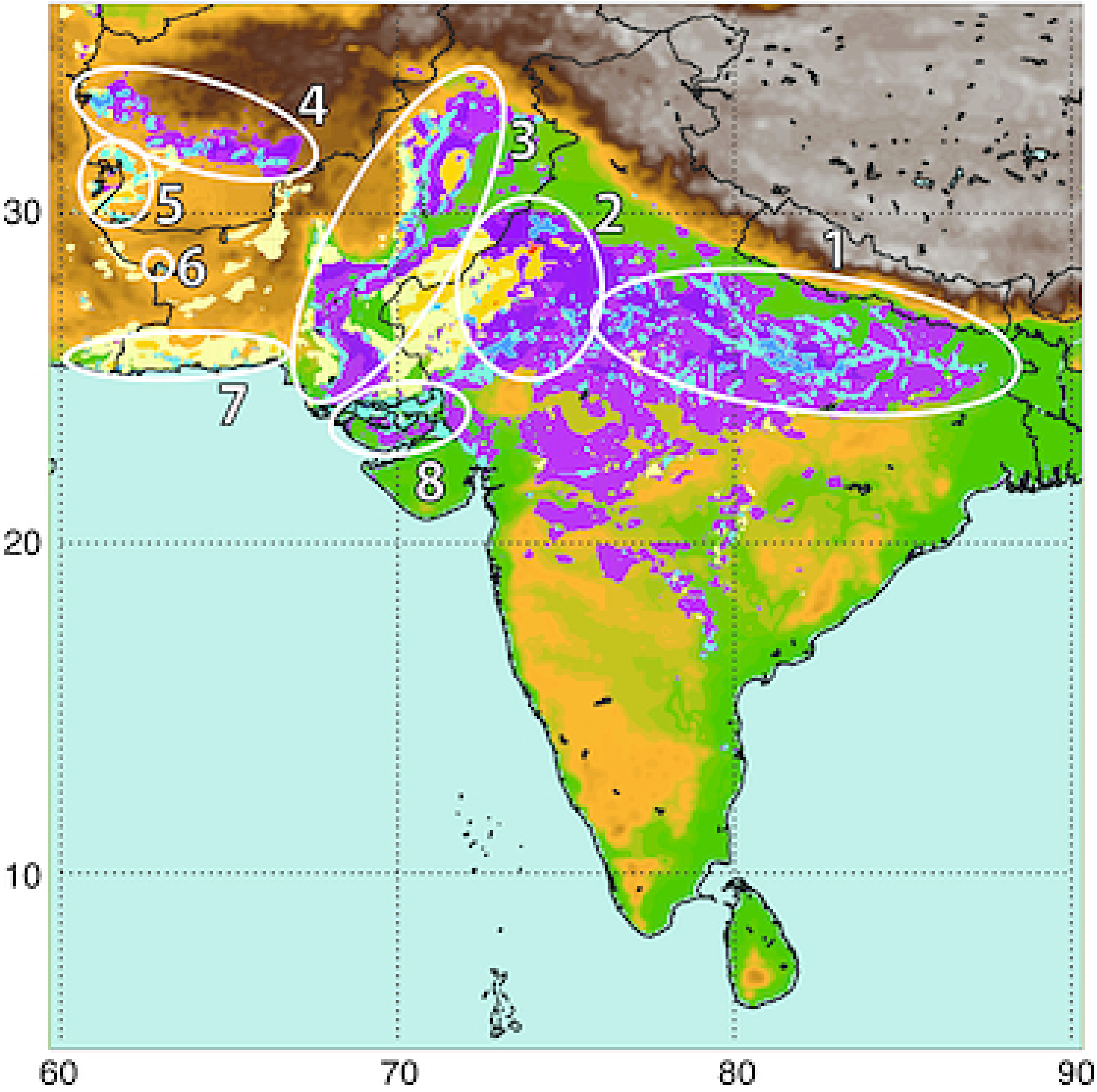
NASA satellite image showing the effects of blasted material transported to the Atlantic Ocean.

Desertification in SW-BAP is thought to result from the interaction of wind erosion vulnerability, recurrent droughts, and inappropriate land management. Controlling desertification in such areas would help mitigate the intensity and magnitude of such large anthropogenic dust sources, which damage habitat at a global scale. Control can only be achieved through local intervention strategies, which require a knowledge of the local dynamics, causes, symptoms and consequences of desertification processes.

In the case of SW-BAP, desertification control will require fundamental changes in production systems and their management, which needs to begin with a change in thinking among producers and decision makers. Recommendations have been made for sustainable livestock and crop production in the area.

Source: Elena M. Abraham, Juan Carlos Guevara and Nelson Darío Soria (Instituto Argentino de Investigaciones de las Zonas Áridas - IADIZA, Mendoza, Argentina)

Figure 3.12: Distribution of the percentage number of days per season (March, April, and May) with Dust Optical Depth > 0.2 over South Asia. The colour shadings are the same as in Figure 3.5. The white circled sources are numbered as follows: 1, Ganges basin in India; 2, desert of Rajasthan in India; 3, Indus basin of Pakistan; 4, southern drainage basin of the Hindu Kush in Afghanistan; 5, ephemeral lakes around the city of Zabol; 6, Hamun-i-Mashkel of Pakistan; 7, Makran coast of Pakistan; and 8, Rann of Kutch in India. Source: Ginoux *et al.* (2012).



3.2.7 Central and East Asia

In Central and East Asia (Figure 3.13) the largest natural sources are associated with basins in China and include the Taklamakan Desert of the Tarim Pendi (location 1), the Qaidam Pendi (location 2), the Hexi corridor, in Gansu province (location 3), the Turpan Pendi (location 10) in Xinjiang Province, and some areas in the Gobi Desert of Inner Mongolia (location 9). The Taklamakan Desert, the largest desert in China and part of the Tarim Basin, receives rivers originating in mountain sediment. Combined with very low levels of precipitation, this provides favourable conditions for a major dust source.

Anthropogenic sources occur mostly in the deserts of Inner Mongolia (location 9), on the Hulun Buir plain (location 8), on the northeast China plains (location 7), within the Junggar Pendi (location 12), and on the margins of the Tarim Pendi (location 1). Farming, overgrazing, and water usage have likely been responsible for the expansion of dust sources in northern China (Xuan and Sokolik 2002), exasperated by drought (Igarashi *et al.* 2011).

There is a significant source of anthropogenic dust in eastern Kazakhstan, the Balkhash-Alakol depression (location 13). Lake Balkhash has been rapidly desiccating since 1970 after completion of a dam on the Ili River (Gill 1996). Over the eastern part of Lake Balkhash and nearby dry lakes, the frequency of observed events is greater than 50% of days. River runoff draining into Lake Balkhash has decreased by half since 1970 due to human activity and this seems to be a general trend for tail-end lakes in flat areas of central Asia (Bai *et al.* 2011). Lake Ebinur located on the eastern part of the Dzungarian basin (location 12) is now a dry lake bed due to human-induced desiccation. The resulting dust contains toxic trace elements (Liu *et al.* 2011).

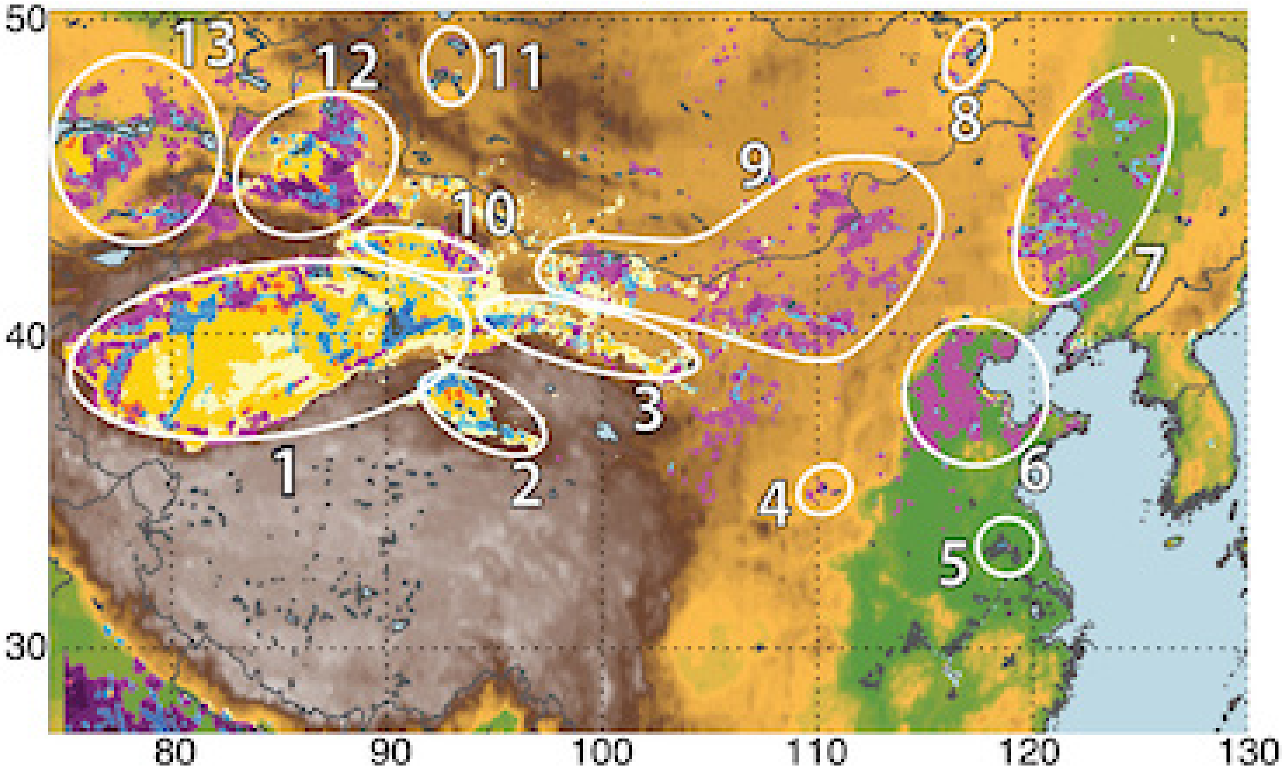
Data from surface meteorological observation stations in China over the past 60 years indicate that there are two regions where dust storm events occur frequently: one centred around Minfeng and Hetian in the South Xinjiang Basin, the other centred around Minqin and Jilantai in the Hexi Region. In the South Xinjiang region, the mean number of occurrences per year was 36 days of dust storms, 81 days of blowing dust, and 208 days of floating dust. The equivalent occurrences for Hexi region were 28 days of dust storms, 96 days of blowing dust and 70 days of floating dust. Dust storms mainly occurred in the arid and semiarid areas of Northern China, whereas the blowing dust and floating dust also extended north-eastwards and south-eastwards. Floating dust mainly extended to the East China Plain and the middle and lower reaches of the Yangtze River and not to the northern regions (Wang *et al.* 2005). The frequency of dust storms, blowing dust and floating dust events in China shows a general decrease from the highest levels during the 1950s and 1960s (Figure 3.14).

Although desertification has increased by only a few percent in China, it has generated disproportionately large areas of enhanced dust emissions (Gong *et al.* 2004). China may contribute up to half of the global production of dust (Zhang *et al.* 1997). Dust storm frequency in China analyses from 1954 to 2005 (Duce *et al.* 1991; Zhou and Zhang 2003) appears to have been at its highest in the 1950s and lowest in the 1990s. For example, records at Beijing and Baotou in Inner Mongolia region show that dust storms were twice as prevalent in the 1950s-1970s compared with the 1970s (Qian *et al.* 2002). The changes have been attributed to climate change impacts (Goudie and Middleton 2006) and tree planting, notably the Great Green Wall (Tan and Li 2015). In some regions of China, such as the Chaidm Basin, dust storm frequency appears to be increasing due to desertification (Wang *et al.* 2004). A recent study of time trends in vegetation index in the Green Great Wall region, which begun in 1978, showed that the Green Great Wall has greatly improved the vegetation index and effectively reduced dust storm intensity in northern China compared with adjacent regions (Tan and Li 2015). The study analysed time trends in Normalized Vegetation Difference Index (NDVI), a measure of green vegetation cover from satellite imagery, together with rainfall and dust storm data from weather stations. An index of dust storm intensity was developed that includes frequency, visibility, and duration of dust events. The effects of climatic change and human pressure were discounted in the study. It was found that NDVI was not related to rainfall trends and dust storm intensity decreased in response to increased NDVI.

Dust from the deserts of China and Mongolia have been found in glacier ice in the north and west of the Tibetan plateau; to the east in Korea and Japan, and across the Pacific Ocean to Hawaii and Alaska; and to the southwest to Taiwan (Goudie and Middleton 2006). Dust from Chinese deserts has travelled 20,000 km across the North Pacific, North America and North Atlantic and deposited in the French Alps (Grousset *et al.* 2003).

In Pakistan the trend in dust storm frequency between 1961 and 2000 shows a decline of 22 to 45% in the period 1991–2000 compared with the preceding period (Hussain *et al.* 2005). The decline may be partly

Figure 3.13: Distribution of the percentage number of days per season (March, April, and May) with Dust Optical Depth > 0.2 over East Asia. The colour shadings are the same as in Figure 3.5. The white circled source areas are numbered as follows: 1, Tarim Pendi; 2, Qaidam Pendi; 3, Hexi corridor in Gansu Province; 4, Tongguan county; 5, Hongze and Gaoyou Lakes of eastern China; 6, North China Plains; 7, Horqin sandy land; 8, Hulun Buir plain; 9, Inner Mongolia deserts; 10, Turpan Pendi; 11, Great Lakes depression in Mongolia; 12, Junggar Pendi; and 13, Balkhash-Alakol depression. Source: Ginoux *et al.* (2012).



attributable to an increase in irrigated land, but dust storm incidence appears to have increased again in the late 1990s due to increased drought conditions.

There is evidence of changes in dust storm frequency as a result of human activity in Russia (Goudie and Middleton 2006). During the Virgin Lands Scheme in the 1950s, about 40 million hectares of steppe pastures were converted to cropland in eastern Russia, western Siberia and Kazakhstan. Dust storm frequency in the Omsk region increased 2.5 fold from 1936-1950 to 1951-1962. An increase in irrigation in Uzbekistan reduced dust storm frequency where vegetation cover was enhanced, but at the expense of the desiccation of the Aral Sea. The Aral Sea bed, which is saline and toxic, became a new dust source (Micklin 1988; UNEP 1995).

3.2.8 Australia

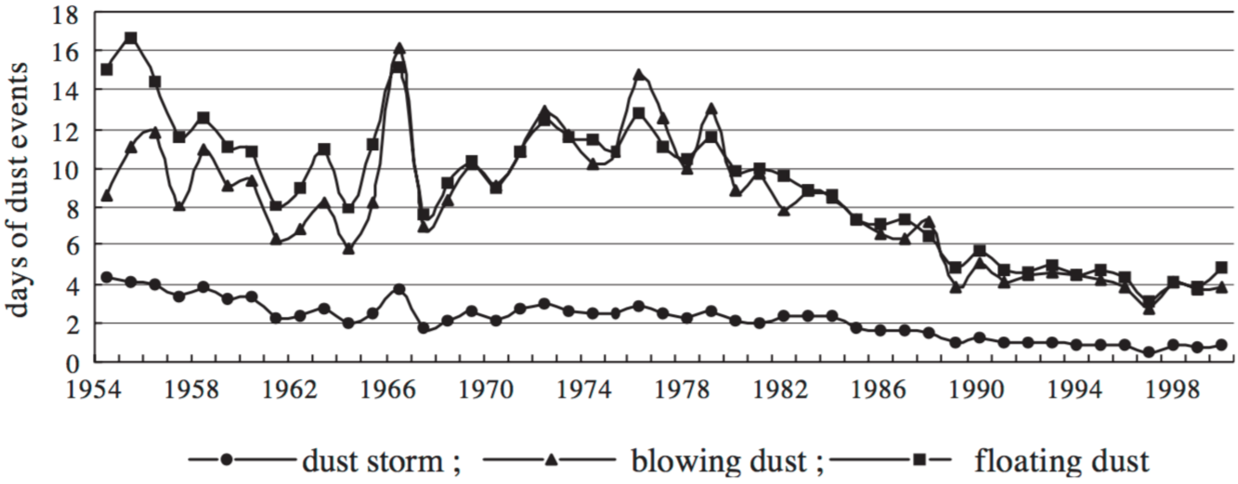
Australia dust sources are concentrated in the eastern half of the continent, in Queensland, Northern Territory, South Australia, New South Wales, and Victoria (Figure 3.15). The northern sources are most active during September to November whereas the southeast sources are most active during December to February. Sources are predominately associated with land use, otherwise with hydrologic features. The percentage of land use in Australia is generally higher than 50% everywhere and often reaches 75% or more (Ginoux *et al.* 2012). The land use is for pasture except in the southwest, whereas cropping is more intensive in the southeast (Murray region).

The most active sources are located within the Lake Eyre Basin (location 4), a large (1.3 million km^2) internal drainage basin, with 60% of dust plumes originating from hydrologic features and 30% from ephemeral lakes (Ginoux *et al.* 2012). Warburton Creek is particularly active (Prospero *et al.* 2002).

The Simpson Desert (location 5) is a large anthropogenic source in Australian spring and can yield very large amounts of dust during major events (Knight *et al.* 1995). While some of the emissions are due to overgrazing, emissions from this remote arid dune field may also be due to massive vegetation losses resulting from fires that start as a consequence of lightning strikes (N. Webb pers. Comm).

There are three major dust sources in the Murray-Darling: the Victorian Big Desert (location 1), the

Figure 3.14: Mean annual frequency of sand and dust storms in China over 60 years from 1954 to 2000. Source: Wang *et al*. 2005.



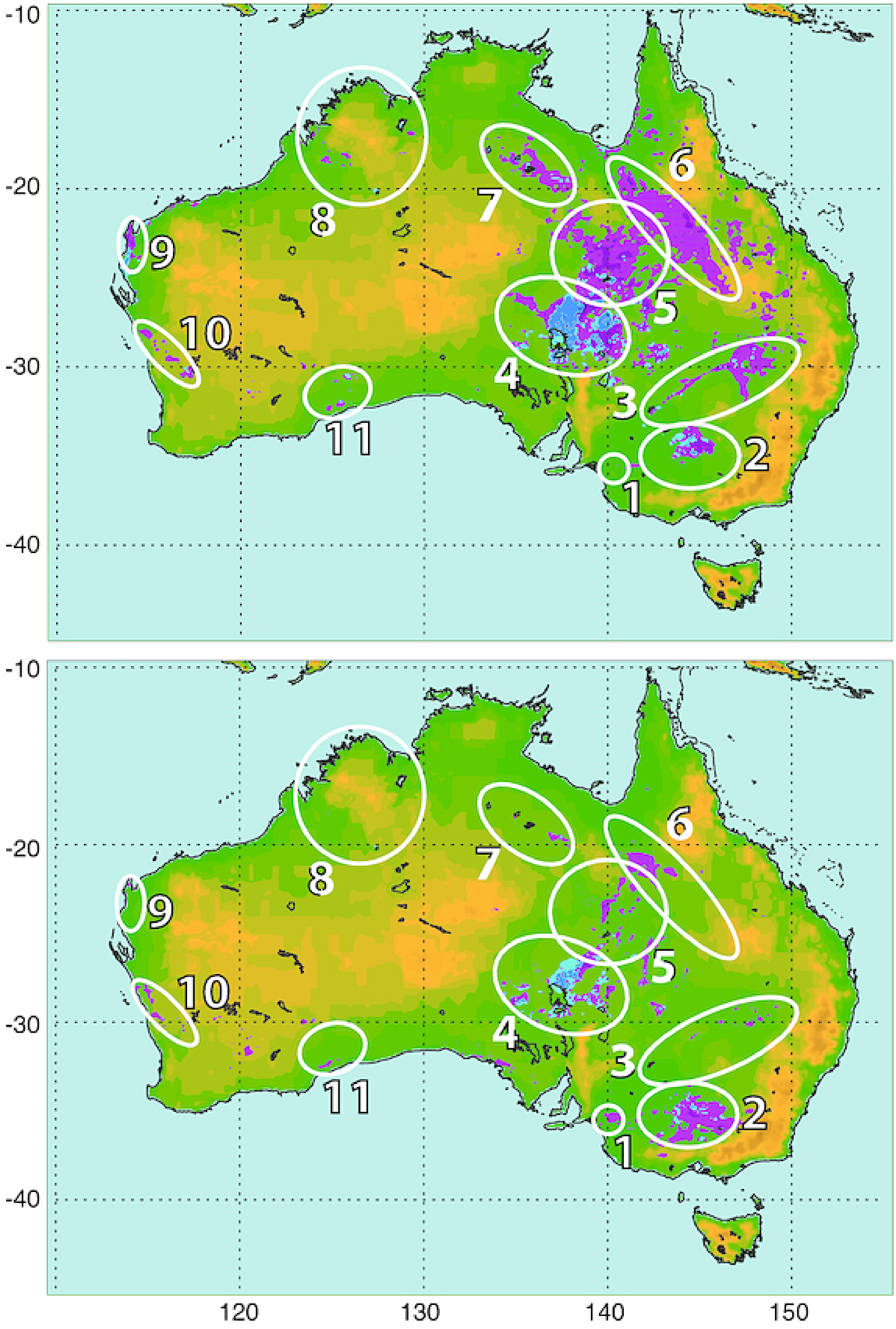
irrigated farmland of Riverina (location 2), and the Barwon-Darling Basin (location 3). The Murray-Darling River systems erode fine particles from the uplands and carry them downriver into the arid zone where they serve as one of the major Australian dust sources (Ginoux *et al.* 2012). The hydrological regime has been disrupted by the increasing demand of water for agriculture and clearing of land, which have led to significant increases in dust deposition on a millennial scale (Marx *et al.* 2011). The ephemeral lakes within the region have not been full since 1976 (Wevill and Read 2010).

The data in Figure 3.15 overlaps the 2001–2007 Australian drought, when the inflow into the Murray-Darling River system was reduced by a factor of three, reaching a historical low (Cai and Cowan 2008). Using the Australian Land Erodibility Model, Webb *et al.* (2006) have shown that during El Niño conditions, there is increased wind erosion in central and south- eastern Australia, while during La Niña years the sources are shifted to the southwestern regions. While Webb *et al.* (2009) show that the story is considerably more complex, with the erodibility of bioregions responding to drought and ENSO in unique ways, often involving lag-responses that are driven by a combination of antecedent climatic conditions, seasonal rainfall variability, and grazing land management.

Australian dust is transported to other regions, eastwards towards New Zealand, and westward into the Indian Ocean, although the latter pathway is less important today (Goudie and Middleton 2006). There is also the potential for a contemporary north-western transport pathway (McGowan and Clark 2008). Although 75% of Australia's emissions are anthropogenic, they only account for 13% of the global anthropogenic emissions (Ginoux *et al.* 2012).

That the entirety of region 6 appears a persistent dust source is surprising as the region (the Mitchell Grass Downs) is productive, generally has high cover of perennial grasses and low erodibility soils (vertosols). This pattern may reflect dust detection downwind of the primary source areas (4 and 5) (N. Webb, pers. comm.). That the Mallee region of northwest Victoria (around "3") and southwest Queensland (around "5") is not included is also surprising. For example, the latter region of the north Strezlecki Desert, Bulloo Basin, and arid Mulga Lands is extremely sensitive to grazing pressure and drought, and frequently has low vegetation cover (and dust storms). Wind erosion in both of these regions is an important contributing factor to land degradation (N. Webb, pers. comm.).

Figure 3.15: Distribution of the percentage number of days per season (top: September, October, and November; and bottom: December, January, and February) with Dust Optical Depth > 0.2 over Australia. The colour shadings are the same as in Figure 3.5. The white circled source areas are numbered as follows: 1, Victorian Big Desert; 2, Riverina; 3, Barwon-Darling Basin; 4, Lake Eyre Basin; 5, Simpson Desert; 6, lee side of Great Dividing Range; 7, Barkly Tableland; 8, Kimberley Plateau; 9, North West Cape; 10, Darling Front Range; and 11, Nullarbor Plain. Source: Ginoux *et al*. (2012).



4. Impacts and Cost of SDS

4.1 Environmental impacts

The effects of sand movement from SDS has mostly local effects on the environment but dust trajectories have global effects on earth processes. Wind erosion can cause soil degradation even without generating SDS and is therefore included here. Feedback effects between land degradation, climate and dust emissions were further described in Section 2.3.5.

4.1.1 Dust and biogeochemical cycles

Dust Storms have both positive and negative global impacts due to their trans-continental reach and the importance of dust in global climate and terrestrial and oceanic biogeochemical cycling (Figure 4.1). The various interactions are complex and not yet fully understood (Knippertz *et al.* 2014). Dust affects atmospheric, oceanic, biological, terrestrial and human processes and systems (Washington and Wiggs 2011). For example, dust plays a major role in the earth's biogeochemical cycles, fertilizing and sustaining both oceans and forests (Goudie 2009).

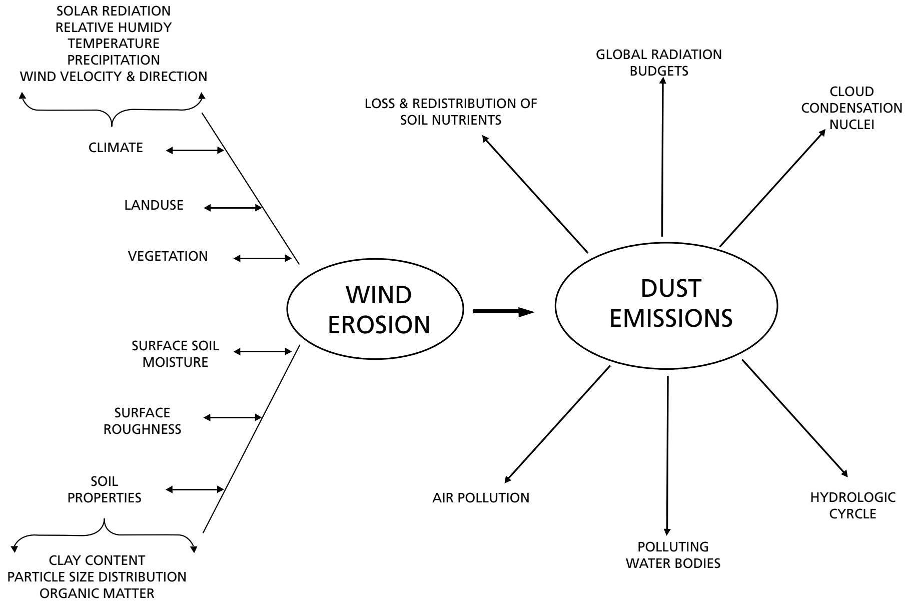
There are a number of mechanisms through which dust influences global biogeochemical cycles. Each year, an estimated 2,000 Mt dust is emitted into the atmosphere, 75% of which is deposited to the land (even though land makes about only about 30% of the Earth's total surface area) and 25% to the ocean (Shao *et al.* 2011). Saharan dust fertilizers the Amazon rainforest, providing a phosphorus input that is comparable to the hydrological loss of phosphorus from the basin (Yu *et al.* 2015). Similarly, Hawaiian rain forests receive nutrient inputs from dust from central Asia, which may sustain forest productivity over long time periods (Chadwick *et al.* 1999). Plant composition in the Colorado Plateau (USA) has been influenced by dust-derived nutrients (Reynolds *et al.* 2001).

4.1.2 Dust and oceans

Dust deposition provides nutrients to surface ocean waters and the seabed, boosting primary productivity, especially through relieving phosphorus limitation to nitrogen fixation, and through iron fixation, which boosts phytoplankton growth (Avila and Penuelas 1999; Jickells *et al.* 1998; 2014; Stuut 2014). Desert dust contains small amounts of iron and is thought to be the dominant source of new iron to some regions of the open ocean (Fung *et al.* 2000). Iron is an important micronutrient in the oceans (Martin *et al.* 1991; Boyd and Law, 2001), and iron deposition has been linked to nitrogen fixation in the oceans (Falkowski *et al.* 1998). Primary productivity in turn affects the global carbon cycle. Ocean phytoplankton is responsible for nearly half the annual CO_2 exchange and a majority of all carbon sequestered over geologic time (Shao *et al.* 2011).

Changes in dust fluxes to the ocean have the potential to modify ocean biogeochemistry (e.g., Moore *et al.*

Figure 4.1: Factors affecting wind erosion and the resultant impacts of dust emissions on the environment. Source: Ravi *et al.* (2011).



2006; Aumont *et al.* 2008). Simulations by Mahowald *et al.* (2010) indicated that that dust deposition trends increased ocean productivity by an estimated 6% over the 20th century.

Dust from Africa and Asia may be adversely affecting coral reefs and other downwind ecosystems in the Americas. Microorganisms, nutrients, trace metals, and organic contaminants deposited in the dust on land and in oceans may play a role in the complex changes occurring on coral reefs worldwide (Garrison *et al.* 2003).

4.1.3 Dust and climate

Dust affects climate through involvement in the biogeochemical cycles (described above), especially through effects on sea blooming and sea surface temperatures (Singh *et al.* 2008), and through physical effects and indirect mechanisms as a result of the dust's chemical reactivity. Dust can modify tropical storm and cyclone intensities (Evan *et al.* 2006).

Dust loadings affect absorption and scattering of solar radiation and can alter the Earth's radiative balance (Highwood and Ryder 2014), affecting both incoming short wave and outgoing long wave radiation (Miller and Tegen 1998). The net effect of atmospheric dust can be one of heating or cooling depending on a number of variables (Arimoto 2001; Miller *et al.* 2014). Changes in the earth's radiative balance can cause drought intensification (Han *et al.* 2008; Highwood and Ryder 2014).

Desert dust can interact with liquid or ice clouds, and thereby modify cloud optical properties and lifetimes (DeMott *et al.* 2003; Mahowald and Kiehl 2003), as well as affect precipitation processes (Creamean *et al.* 2013). Dust affects cloud formation and characteristics and dust nuclei may inhibit precipitation by making more and smaller water droplets, or increase it by acting as nuclei for ice particles (Nenes *et al.* 2014; Toon 2003). Dust can also affect precipitation indirectly through effects on convective activity as a result of altered temperature gradients (Maley 1982).

The deposition of mineral dust on glaciers has the potential to lower their surface albedo and speed up their melting (Oerlemans *et al.* 2009). Mineral dust affects tropospheric ozone, reducing photolysis rates of ozone production by as much as 50% and providing reactive surfaces that support processing of trace gases (Martin *et al.* 2003). Feedback effects between land degradation, climate and dust emissions were further described in Section 2.3.5.

4.1.4 Wind erosion, SDS and land processes

Wind erosion is a major land degradation process, especially in arid and semiarid regions (Blanco and Lal 2010; Goudie and Middleton 2006). Wind erosion can have damaging environment effects even without producing SDS. Wind erosion preferentially removes finer soil particles, which constitute the most active soil component in retaining nutrients and organic matter, resulting in degradation of chemical, physical and biological soil properties, reduced soil productivity and impaired capacity to provide other ecosystem services, such as hydrological and climate regulation (see Section 2.3.3). The eroded material may cause mechanical injury to crops and natural vegetation by abrasion and blown sand may bury young plants (Ravi *et al.* 2011).

Deposition of dust particles on plant surfaces may affect photosynthesis (Squires 2016) and also act as a desiccant reducing the drought tolerance of plants (Burkhardt 2010). Eroded materials may also contain pollutants and plant pathogens (Goossens 2003). SDS have been reported to cause livestock deaths. Sand deposition along fence lines and in drainage ditches in agricultural areas can result in high recurring maintenance costs.

Dust deposition has played a role in soil formation in many parts of the world, often at large distances from desert margins. The most striking example is the influence of aeolian processes on the formation of loess soils (unconsolidated silt), which occur extensively in North and South America, Central Asia and China (Goudie and Middleton 2006; Muhs *et al.* 2014). Aeolian processes have also contributed to the formation of stone pavements and duricrusts, as well as soil salinization and alkalinity, through accumulation of soluble salt, and reduction of soil acidity through addition of carbonates (Goudie and Middleton 2006). While wind erosion may expose soil organic matter to increased decomposition, deposition of soil in deep sediments can also protect soil organic carbon from decomposition (Jacobs and Mason 2005).

In conclusion, the large uncertainty over the effect of future changes in land use and management and climate change on SDS and dust emissions, with large regional variations (see Section 2.4.3), coupled with the uncertainty in dust feedback effects on the environment, indicate potentially large but highly uncertain impacts on the environment. Indeed, modelling studies indicate a high sensitivity of dust emissions to human intervention, with large implications for climate and biogeochemistry in the future (Mahowald *et al.* 2010). Given this sensitivity and the large potential effects on the environment, precautionary principles should be applied and action taken to minimise human-induced sources of dust emissions.

4.2 Human health impacts

4.2.1 Overview

Human health impacts are due to the physical, chemical and biological properties of airborne dust. Substantial amounts of airborne mineral dusts are respirable within aerodynamic size ranges, defined by the US Environmental Protection Agency, of fine particles of equal to or less than a diameter of 2.5 microns (PM2.5) and coarse particles of between 2.5 and 10 microns (PM2.5 - PM10). PM10 refers to particles of less than or equal to a diameter of 10 microns. Inhalation of these fine particles is a health hazard.

From summary reports, such as from the World Health Organization (WHO 2013), we find that particle pollution, including dust, affects more people than any other pollutant, as there is no safe threshold below which exposure to these mixtures of organic and inorganic chemicals and substances do not threaten health. Chronic exposure to fine particulates is associated with premature death due to cardio-vascular and respiratory disease, lung cancer, and acute lower respiratory infections (e.g., pneumonia). Inhalation of fine dust particles exposes individuals not only to hazardous fine mineral particulates, but also to harmful combinations of pollutants, spores, bacteria, fungi, and potential allergens carried along with mineral dusts (Kellogg *et al.* 2004; Smith *et al.* 2011). Dust particles can adsorb anthropogenic atmospheric pollutants during transport (Onishi *et al.* 2012) including ammonium, sulphate and nitrate ions and heavy metal compounds not believed to originate from the soil. Thus, exposure to windblown dust is increasingly linked to a range of health problems.

Acute and long-term exposure to these dusts can have a range of serious health effects. Yet, while the global burden of human health impacts of airborne mineral dust and dust storms is presumed to be significant, the subject has lacked the kind of attention given, for example, to the health effects of aerosol emissions from industry, energy generation and transportation. Few long-term systematic studies have been conducted of health consequences in major dust source regions (De Longueville *et al.* 2013), even though dust levels all too often far exceed air quality standards (Ginoux *et al.* 2012). For example, Brown *et al.* (2008) report annual mean values of PM10 concentration in Kuwait ranging between 66 to 93 µg/m^3 (31 to 38 µg/m^3 for PM2.5), both well above the World Health Organization air quality guidelines of 20 µg/m^3 annual mean for PM10 and 10 µg/m^3 for PM2.5 (WHO 2006).

Exposure to dust particulates irritates the respiratory tract and is associated with respiratory disorders, such as asthma, tracheitis, pneumonia, aspergillosis, allergic rhinitis and nonindustrial silicosis, known as "desert lung" syndrome (Derbyshire 2007). Dust can cause or aggravate diseases such as (i) bronchitis, (ii) emphysema (damage of the air sacs in lungs), (iii) cardiovascular disorders (e.g., stroke), (iv) eye infections (Chien *et al.* 2014), (v) skin irritations, (vi) meningococcal meningitis (Pérez Garcia Pando *et al.* 2014), (vii) Valley fever (Laniado-Laborin 2007; Sprigg *et al.* 2014; Williams *et al.* 1979), and (viii) diseases associated with toxic algal blooms. It can also cause mortality and injuries related to reduced visibility and highway accidents (Goudie 2014).

Health consequences are worldwide, particularly affecting populations in arid and adjacent areas including, for example, in the Middle East (Thalib and Al-Taiar 2012), North Africa, the Sahel and Australia (Merrifield *et al.* 2013), China (Yan *et al.* 2012), and the US Southwest and Mexico (Grineski *et al.* 2011). Populations far from the source regions are exposed when long-range atmospheric transport carries dust, for example from China and Mongolia to Japan and Korea (Hong *et al.* 2010). Asian dust is shown to contribute to aerosol loadings in western North America (Fairlie *et al.* 2007). African dust transported to the Caribbean and Florida (Prospero and Lamb 2003) has triggered violations of US air quality standards and makes up about half the airborne particulates in South Florida's air during the summer (Prospero and Mayol-Bracero 2013).

Populations particularly vulnerable to airborne and respiratory diseases in all countries are children and the elderly, people with pre-existing heart and lung diseases (e.g., asthma, chronic obstructive pulmonary disease, ischemic heart disease, and allergies) and outdoor labourers in high exposure situations.

4.2.2 Specific conditions

Cardio-vascular issues

The World Health Organization (WHO 2013) links cardiovascular hospital admissions and mortality to windblown dust. This is backed by a growing number of studies that show mineral dust emissions from arid lands contribute to many respiratory and cardiovascular illnesses (e.g., Gianndaki *et al.* 2014; Goudie 2014; Morman and Plumlee 2013).

Dust reaching Taiwan from mainland Asia has been associated with increased risk of heart disease (Bell *et al.* 2008) caused by a restriction in blood supply to tissues (ischemia). In Taiwan, a study of 39 Asian Dust Storm events found drastic increases in cardiopulmonary emergency visits when ambient PM10 concentrations were high, increasing cardiovascular diseases visits by 67%, ischaemic heart diseases by 35%, cerebrovascular diseases by 20%, and Chronic Obstructive Pulmonary Disease (COPD) visits by 20% during high dust events, compared to pre-dust periods (Chan 2008). Similarly in Japan, Asian Dust clouds have been reported to increase emergency room calls for cardio-vascular stress by 21% (Ueda *et al.* 2012). In 2005, a dust storm in Baghdad led to nearly 1000 cases of suffocation (Goudie and Middleton 2006).

Respiratory Disease and Asthma

Epidemiological studies in Italy (Sajani *et al.* 2011) and Spain (Jiménez *et al.* 2010) found increased respiratory mortality among the elderly during Saharan dust events. Dust entering El Paso (Texas) from the Chihuahuan Desert has increased hospital admissions for asthma and bronchitis, especially for children (Grineski *et al.* 2011). Because asthma is one of the world's leading non-communicable diseases, affecting 334 million people every year (Global Asthma Report 2014), special attention is paid to the potential role of airborne mineral dusts in causing or exacerbating asthmatic conditions.

Asthma is a chronic airway disorder, where inflammation and contraction of small muscles around the respiratory system's airways restrict the flow of air. It has a variety of causes, including inhalation of pollen, mould and dust. The greatest risk factor for developing asthma is to inhale particles such as dust that irritate the airways or provoke allergic reactions (WHO 2013). Biological responses to desert mineral dust have been found in human respiratory epithelial cells (Ghio, *et al.* 2014), an effect also seen in mouse respiratory tract injuries following dust inhalation.

Benefitting from continuous dust measurements conducted in Barbados by the University of Miami since 1965, researchers have been able to explore the possible relationships between airborne dust and asthma in the Caribbean (Prospero and Lamb 2003). The Caribbean Allergy and Respiratory Association found that asthma has increased 17-fold in Barbados and Trinidad since 1973 (Prospero and Mayol-Bracero 2013; Shinn *et al.* 2000). More patients attend accident and emergency departments across the Caribbean in the rainy season (mid-May to December) than in the dry season (January to mid-May). The number of admissions in accident and emergency departments across the Caribbean rises sharply and starts from September to November or December from Trinidad in the south to Antigua in the north (Monteil 1998). The Caribbean rainy season coincides with a maxima of Sahara dust transported across the Atlantic, but proof of a link between Sahara dust and Caribbean asthma is elusive.

Increases in dust from the early 1970s roughly parallel a significant increase in regional asthma in the Caribbean (McCarthy 2001) but other researchers raise evidence that Saharan dust over Barbados was likely not a factor (Prospero *et al.* 2005; 2008). Even though Africa dust often contains fungal spores, the effect of spores and pollen from local sources dominate asthmatic hospital visits (Blades *et al.* 2005).

On the other hand, others have identified increased emergency paediatric asthma admissions with increased Saharan dust over Trinidad, concluding that the influx of pollutants, microorganisms, pollens and dust from Saharan dust clouds cannot be ignored (Gyan *et al.* 2005; Mohamed *et al.* 2006). In the archipelago of Guadeloupe in 2011, increased asthma-related emergency room visits were found for children from ages 5 to 15 years following exposure to Sahara dust of PM10 and PM2.5–PM10 (Cadelis *et al.* 2014). The authors noted no statistical difference in risk among other age groups of children and between boys and girls for PM10 and PM2.5–PM10.

Epidemiological studies have shown that increases in allergic rhinitis (Chang *et al.* 2006) and daily admissions and clinical visits for allergic diseases such as asthma coincided with Asian dust storms (Kanatani *et al.* 2010; Ueda *et al.* 2010; Yang 2011). Children are particularly vulnerable. Their exposure to dust particles transported globally from desert storms is associated worldwide with increased hospital admissions for childhood asthma and bronchitis, for example in Japan (Kanatani *et al.* 2010), Trinidad (Gyan *et al.* 2005) and Texas (Grineski *et al.* 2011). In Qatar, asthma cases are reported to increase by 30% during and shortly after very windy conditions (Teather *et al.* 2013). Worsening asthma symptoms caused by Asian dust may be attributed to combined particulate matter and air pollutants (Watanabe *et al.* 2011), or associated with plural allergic reactions triggered by dust exposure (Otani *et al.* 2012; 2014).

Valley fever

In addition to aspergillosis (Chao *et al.* 2012), airborne dust-associated fungal diseases include coccidioidomycosis, or "Valley fever" (Williams *et al.* 1979). There are several endemic hotspot of Valley fever in drylands, particularly southwest US, northern Mexico and northeast Brazil. The soil-dwelling fungal spores (*C. immitis* and *C. posadasii*) associated with valley fever, or coccidioidomycosis (cocci), are carried along with the desert dust, ready to be inhaled and infect (Pappagianis and Einstein 1978). On average each year 150,000 people contract Valley fever, whereas 30 people die from it in Arizona (ADHS 2012) and 70 in California (Flaherman *et al.* 2007). Arizona Hospital Discharge Data show 1,735 hospital visits for Valley fever in 2007, resulting in USD 86 million in hospital charges alone (Tsang *et al.* 2010). The full scope of the problem is unknown. Surveillance for cocci is difficult and few details exist except on its general endemic range in the Americas (Hector and Laniado-Laborin 2002; Ochoa 1967).

Dust, presumably with 'hitchhiking' cocci spores, can be carried over considerable distance (Litvintseva *et al.* 2014; Sprigg *et al.* 2008; Sprigg *et al.* 2014). Significant amounts of dust cross the border into Texas from Mexico during typical dust events in the region and dust sources in the US also affect Mexico's air quality (Yin and Sprigg 2010). Yet, it is unknown how long in the free atmosphere the cocci spore can remain viable. In one study, spores blown in a storm from California infected people in Oregon (Barker 2012).

Meningococcal Meningitis

Meningococcal Meningitis, also known as cerebrospinal meningitis, caused by the bacterium *Neisseria meningitides*, can cause large epidemics with fatality rates among cases. It is spread by person-to-person contact through respiratory droplets (throat secretions) of infected people (WHO 2015). Substantial research in highly affected areas show seasonal occurrence of cases is correlated strongly with levels of low humidity and high concentrations of airborne dust during the dry season (Abdussalam *et al.* 2013; Agier *et al.* 2013; Cuevas *et al.* 2007) and outbreaks rapidly decline with the onset of the rainy season (Molesworth *et al.* 2002). Although the environmental linkages of transmission are not fully understood, it is assumed that dust inhalation damages the pharyngeal mucosa and facilitates bacterial invasion.

Epidemics can occur worldwide. However, the largest mainly occur in the African "meningitis belt," a semi-arid region spanning the Sahel from Senegal in the west to Ethiopia in the east (26 countries), which has the highest rates of the disease (WHO 2015). Since the successful roll-out of the Group A meningococcus conjugate vaccine from 2010, over 220 million persons have received the vaccine in 15 countries, and the *Neisseria meningitidis* serogroup A is disappearing, although other meningococcal serogroup epidemics still occur at a lower frequency and smaller size (WHO 2015).

The timing of major meningitis outbreaks and dust storms from the Sahara appear highly correlated. Noinaj *et al.* (2012) hypothesize that Neisseria bacteria, responsible for meningitis, need iron-laden dust to grow and become virulent. Predicting and simulating windblown dust helps to understand whatever role mineral dust may play in meningitis outbreaks across Africa (Pérez Garcia Pando *et al.* 2014; Thomson *et al.* 2006; 2009). International organizations including WHO, WMO and the Group on Earth Observations (GEO) support research with many African countries in the "Meningitis Environmental Risk Information Technologies" project (MERIT 2014), where the SDS-WAS has provided observations, forecasts and simulations of airborne dust and dust storms to assess risks and attribution, and cause and effect. With an understanding of the seasonality of dust forcing on meningitis, it is now possible to predict seasonal outbreaks by estimating dust aerosols and inform how to best target vaccination campaigns (Pérez Garcia Pando *et al.* 2014).

Eye and Skin Infections

The influence of Asian dust on eye and skin infections has been documented to trigger conjunctivitis (Yang 2011), itchy eye and skin. Although the symptoms are not as severe, dust effects on nasal congestion and sore throat are also reported in otherwise healthy individuals (Otani *et al.* 2011).

4.3 Economic impacts

SDS have wide ranging economic impacts, both immediate and long-term (Table 4.1; Box 4.1; Box 4.2). Not included in Table 4.1 are positive economic impacts, such as fertilization of forests and positive climate regulation effects described in Section 4.1. Longer-term impacts of SDS are less well documented than immediate impacts. The removal of accumulated sand and dust from main infrastructures can be costly (Table 4.2) and damage to crop lands can be extensive (Table 4.3).

In the USA, the negative off-site impacts of erosion from farms are potentially greater than onsite losses in soil productivity. For example, by the mid 1980s,

Table 4.1: Economic impacts of sand and dust storms

Immediate term	Long-term
Immediate human health problems (e.g., respiratory problems) and mortality	Cumulative human health problems (e.g., bronchitis, cardiovascular disorders)
Annual and perennial crop damage	Soil erosion and reduced soil quality
Livestock mortality	Soil pollution through deposition of toxic biological materials (fungi, bacteria), heavy metals, or salts
Infrastructural damage (e.g., buildings, electricity and telephone structures, power facilities, solar farms, machinery, greenhouses)	Disruption of global climate regulation (through feedbacks involving global warming, ocean productivity and CO2 production, precipitation changes, global ice volume, sea level, hydrological cycle, and vegetation cover)
Costs of clearing sand and dust from infrastructure (e.g., roads, airports, dams, irrigation canals, flood control structures, ditches, power facilities)	
Interruption of transport (air, road, rail) and communications; air and road traffic accidents	

Source: summarized from Goudie and Middleton (2006).

Table 4.2: Cost of removal of blown sand from infrastructure in the Middle East.

Area	Reference	Year	Cost (USD) of sand removal per cubic metre
Kuwait	Al-Dousari, *et al.* (in press)	1993	1.80
Kuwait	Al-Dousari, *et al.* (in press)	2013	5.33
Hafouf, Suadi Arabia	Alghamdi and Al-Kahtani (2005)	2004	0.50
Sistan, Iran	Pahlavanravie *et al.* (2012)	2000	2.00
Sistan, Iran	Pahlavanravie *et al.* (2012)	2004	0.50

off-site costs associated with wind erosion in the State of New Mexico were estimated at USD 466 million per year, dwarfing the USD 10 million per year on-site costs (Huszar and Piper, 1986). In South Australia, off-site economic impacts of wind erosion were estimated at between AUS$11 million and AUS$56 million, mostly due to health impacts (Willams and Young 1999).

The economics of preventive measures have received very little attention, perhaps because preventive measures, such as increased vegetation cover in source areas (Section 2.3), need to cover large land areas and take many years to implement and take effect. However, parallels with intervention strategies in public health (Shepherd *et al.* 2015) suggest that bringing down the average level of key risk factors in the population as a whole (in this case all vulnerable land) could be the most cost effective strategy for reducing the future burden of SDS impacts.

Dust storm outbreak affecting Riyadh, Saudi Arabia, on 10 March 2009 at 09:00 UTC, showing a weather frontal system (left) (source: Meteosat-9): the dust storm disrupted flights at the city's King Khalid International Airport and the weather authorities announced that visibility dropped to zero (Photo credit: Jad Saab).

Dunes migrate across a newly built road (Photo credit: David Thomas).

Table 4.3: Economic losses caused by SDS in spring in northern China for the period 2010-2013.

	2010-2013		
Province	No. of storms	Affected cropland (1000 hectares)	Economic losses (USD millions)
Xinjiang	7	23	666
Inner Mongolia	3	600	67
Gansu	10	296	220
Ningxia	1	6	2
Shaanxi	1	3	9
Total	22	928	964

Converted from CNY at average rate for the period of USD 1 = CNY 6.4
Source: Yearbook of Meteorological Disasters in China (2011-2014), China Meteorological Press.

Box 4.1: Economic impact of SDS in South Korea.

South Korea is affected by dust originating from northeast Asia, especially Inner Mongolia, mostly in the spring. Earlier, when agriculture prevailed in the Korean peninsula, SDS were viewed positively, playing some role in enhancing agricultural productivity through soil enrichment. However, with industrialization over the past few decades, SDS have begun to cause economic damage. In a survey of enterprises in South Korea, 56% of enterprises responded that they are negatively affected by SDS (Choo *et al.* 2003). The semiconductor, electronics and air transportation industries are particularly affected.

In 2002, the Korean air transportation industry recorded sale losses due to flight cancellations caused by SDS of USD 0.6 million. In the same year the country was estimated to have incurred costs of USD 4.6 billion, 0.8% of GDP, when medical expenses, opportunity costs and industrial damage were included (Kang *et al.* 2004). However another study concluded that losses were partly offset due to benefits from medicine and indoor leisure industries amounting to USD 3.18 billion (Kim 2009). Further scientifically sound and socio-economically robust studies are required to provide a more accurate assessment.

Box 4.2: Impact of a strong sand storm in Northwest China, May 5, 1993

Driven by a cold air current from Siberia, a severe sandstorm occurred in northwest China in early May 1993. It moved southward from May 4 to 6, 1993, affecting a total area of 1.1 million square km, including northern Xinjiang to western Gansu, western Inner Mongolia and most of the Ningxia Hui Autonomous Region. The wind speed reached 37.9 m/s (average wind speed was 21 m/s), and the visibility was less than 50 m. Total suspended particle concentration reached 1,016 mg/m^3 (40 times higher than the acceptable health standard).

The sandstorm caused great losses. A total of 85 people died and 264 were injured, mostly primary school children in Wuwei area (see below), 4,412 houses were destroyed and 120,000 animals died or went missing. About 373,333 million hectares of crops were destroyed, over 2,000 km of irrigation ditches were buried, ground transportation (train and highways) was suspended, and telecommunications facilities were severed damaged in some areas. The direct economic losses reached 550 million CNY (USD 96 million in 1993).

Meteorological agencies and local authorities put out warnings by radio and other means, but some primary school teachers had poor knowledge of sandstorm preventive measures and asked the pupils to go home, rather than staying in the school until after the storm. The sandstorm hit when the pupils were on the way home. Some of them sheltered behind a wall but were killed when the wall collapsed. Others were drowned in a water diversion canal, which ran next to the road. This illustrates the importance of promoting public awareness of emergency measures during sandstorms.

Source: Zhang and Wang (1997).

5. Monitoring, Prediction and Warning Systems for SDS

There are many complementary ways of monitoring dust. Satellite products are widely used, validated with ground measurements (Table 5.1) combined with numerical modelling. Satellite products have the advantages of large spatial coverage (regional to global) and regular observations, which can be made available to weather centres and other institutions in Near-Real-Time (NRT) (Benedetti *et al.* 2014). Shortcomings include the highly integrated nature of satellite measurements, not only over the atmospheric column but also over all aerosol components, and the low aerosol detectability over bright surfaces, which affects instruments operating in the visible part of the spectrum. The generation of high-resolution infrared spectrometers and interferometers on polar-orbiting satellite platforms, such as the Inertial Altitude Reference System (IARS) and the Infrared Atmospheric Sounding Interferometer (IASI), have the potential to provide good quality dust information (Peyridieu *et al.* 2010; Klüser *et al.* 2011; Hilton *et al.* 2012), but they present at insufficient time resolution. The latest generation of satellites provide a vital tool for real-time dust monitoring: they combine the specific advantages of geosynchronous, or polar, orbits (high time resolution over a wide geographic domain) with the geometric, radiometric and spectroscopic capabilities of high resolution radiometers.

In-situ measurements of air quality through monitoring networks are the main surface data source. As with the satellites, air quality measurements integrate the contribution of the different types of atmospheric aerosol. Furthermore, observational values are usually limited to the concentration of particulate matter with an aerodynamic diameter less than 10 µm (PM10), which does not always encompass the full size range of dust particles suspended in the atmosphere. It is important to consider the selection of stations used for dust monitoring, since many of them are located in cities, industrial parks or roads, where local human activity is the main source of particles, obscuring the contribution of dust to measured quantities. Air quality networks perform systematic measurements with high spatial density in developed countries, but not in developing countries. In addition they are very sparse, discontinuous and rarely available in near-real-time close to the main dust sources. Furthermore, there is no protocol for routine international exchange of air quality data, so their use is often limited to national level.

The WMO Global Atmosphere Watch (GAW) Programme (GAW 2016), as an international body, is providing international protocols to cover this gap: The GAW Aerosol Programme strives "to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality up to multidecadal time scales". The Programme aims to enhance the coverage, effectiveness, and application of long-term aerosol measurements within GAW and with cooperating networks worldwide, by (i) further harmonizing aerosol measurements, (ii) promoting coordination of networks for in situ observations, (iii) establishing a GAW aerosol lidar (light detection and ranging) network in cooperation with existing networks, (iv) contributing to the integration of satellite, aircraft, and surface-based aerosol observations with aerosol modelling, (v) encouraging greater data submission and utilisation of GAW aerosol data, and (vi) supporting near-real-time exchange of aerosol data. The vision of the aerosol programme is comprehensive integrated sustained observations of aerosols on a global scale through

Table 5.1: Overview of observing systems for SDS.

Observing system	Products
In-situ measurements (i.e. air quality monitoring stations)	Aerosol mass concentration (PM10, PM2.5)
Meteorological stations	Visibility, present weather
Sun-photometers (i.e. AERONET and CARSNET networks)	Total-column aerosol optical and microphysical properties
Ground-based lidar/ceilometers (different networks coordinated by GALION)	Vertical profiles of aerosol optical and microphysical properties
Meteorological satellites	Composite images where dusty areas are highlighted (i.e. EUMETSAT RGB Dust)
	Aerosol index (semi-quantitative retrievals)
	Total-column aerosol optical and microphysical properties (quantitative retrievals)
Satellite-borne lidar	Vertical profiles of aerosol optical and microphysical properties

a consortium of existing research aerosol networks, complementing aircraft, satellite and environmental agency networks (GAW Report No. 207). The GAW aerosol network consists of 28 Global Stations and over 200 fully operational Regional and contributing stations (GAWSIS 2016). The GAW stations serve as regional reference stations.

Visibility data included in meteorological observations have been used as an alternative source of information (Shao *et al.* 2003) and give much greater historical depth than satellite data, some spanning more than 100 years. Visibility is mainly affected by the presence of aerosol and water in the atmosphere. Therefore, 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 (fog, rain, etc.). Several empirical relationships between visibility and dust surface concentration can be found in the literature (D'Almeida 1986; Mohamed *et al.* 1992; Shao *et al.* 2003; Camino *et al.* 2015). However, the validity of these relationships is limited, because visibility reduction depends not only on the dust mass concentration, but also on the size spectrum of particles, as well as their density, chemical and mineralogical composition, and atmospheric humidity; although these factors do also affect satellite data.

Direct-sun photometric measurements are a powerful remote sensing tool that provides retrieval of column-integrated aerosol microphysical and optical properties. In particular, The Aerosol Robotic Network (AERONET) is a comprehensive set of continental and coastal ground-based sun/sky scanning radiometers complemented with several sparsely distributed oceanic stations that provides large and refined data sets in near-real-time (Holben *et al.* 1998; Dubovik and King 2000). Integral parameters such as aerosol optical depth are complemented with spectral information. A major shortcoming of these measurements is their unavailability under cloudy skies and during night time. Dual polarized radar has proved to be useful in detecting tornadoes, hurricanes, winter storms, supercell developments that can lead to high surface winds and have capability to detect non-meteorological targets including suspended dust particles (NOAA 2013).

Lidar and the most recent generation of ceilometers permit routine measurement of aerosol vertical profiles. However, continuous measurements in ground-based stations are only performed in a few stations that are, in general, far from the main dust sources. On the other hand, space-borne lidars (e.g., Cloud-Aerosol Lidar with Orthogonal Polarization – CALIOP) provide global spatial coverage, although their temporal resolution is limited.

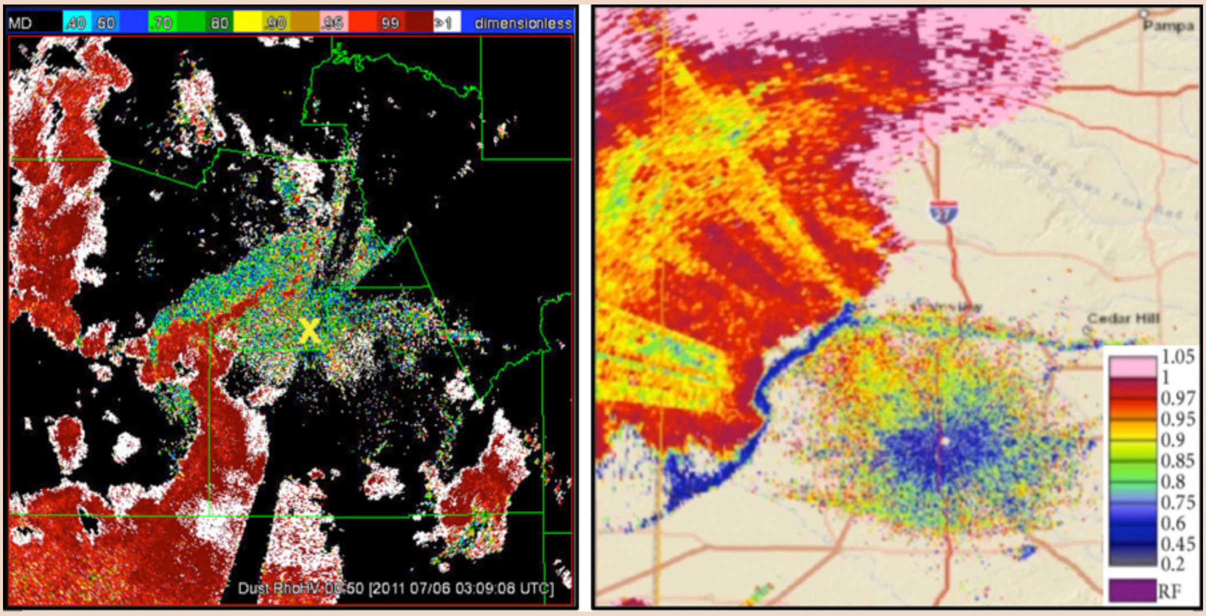
Benedetti *et al.* (2014) provide a good overview of the history of dust forecasting, which is summarized here. Westphal *et al.* (1987; 1988) were the first to use a multidimensional, size-resolving, full physics, numerical dust transport model, which demonstrated the practicality of numerical simulations of dust storms. In the following years, this concept was developed into capabilities for operational dust forecasting. Between 1991 and 1993, the predecessor version of the DREAM dust model (Nickovic and Dobricic 1996) was the first regional model in which dust concentration was built into the prognostic equations of the atmospheric model driver. Experimental daily dust forecasts were performed in Tunisia (1995) using the Dust Regional Atmospheric Model (DREAM) and then in Greece (1996-1997) using the SKIRON system, a weather forecasting model, operated by University of Athens, which gives three days weather forecast in the Mediterranean region (Kallos *et al.* 1997). Then, the U.S. Navy developed the Navy Aerosol Analysis and Prediction System (NAAPS), which includes dust, smoke and sea-salt. In 1999 it became the first fully operational aerosol model. Since then, operational forecasts have become available from a number of numerical weather prediction and research centres around the world. Numerical models contributing to SDS-WAS are given in Table 5.2.

Box 5.1: Dual polarized radars in detecting sand and dust storms

Dual-pol technology enables radar data to provide a two-dimensional measure of particles that reflect the signals. Dual polarized radars send out both horizontal and vertical pulses of energy, which are reflected back to radar by particles in the atmosphere (cloud ice/droplets, precipitation or some non-meteorological particle or object). Obtained data can provide forecasters a measure of the size and shape of the object. Some of the evident benefits in using dual polarized radars are: significant improvement in estimation of precipitation amounts. They can distinguish the type of precipitation (rain, hail, snow) and can detect non-weather particles/objects like dust, etc. In general, they better equip forecasters to issue more precise and detailed warnings, and significantly contribute to reducing the impact of hazards, reducing costs and saving lives.

NOAA's National Weather Service (NMS) in 2013 completed an upgrade of Doppler radars using dual-polarization technology (NEXRAD network), which includes 122 NWS radar sites in USA.

Employing radar reflectivity factors alone (as is done with single polarization radars) limits microphysical interpretation. Two sampling volumes, one containing a large concentration of small particles and the other a smaller concentration of large particles, can have similar values of reflectivity. Dual-pol technology allows distinction between this two to be made using a *co-polar correlation coefficient* (*ρhv*), which is a measure of the correlation between the backscattered horizontal and vertical polarized signals from each scatterer within a sampling volume and depends on particle shape and orientation. For spherical particles *ρhv*≡1, for pure rain it is very close to 1, for irregular scatterers (hailstones with large protuberances, chaff, debris) the values decrease, and values bellow 0.8 in general indicate non-meteorological targets. Considering *ρhv* values during the dust storm, it is shown that values of about 0.5 recognize well airborne dust as a scatterer. Thus, dual-polarized radar *ρhv* data with low values can be considered as very good indicator of dust storms.



Dual-polarized radar values of correlation coefficient for haboob events: 5 July 2011 Phoenix, AZ (left) and 5 June 2013 Lubbock (TX). Source: Vukovic *et al*. (2014), Dempsey (2014).

The co-polar correlation coefficient in combination with reflectivity and Doppler velocity can detect the development and progression of severe dust storms (for example haboobs). Bearing in mind that ground observations are scattered and insufficient for detection of dust storm size, shape and timing, and that satellite data are not always available, use of dual-pol radar data may provide an important scientific contribution to improving knowledge on dust storm nature and in developing numerical models for SDS prediction. The use of dual-polarized radars can be considered as significant upgrade and a promising tool in SDS warning, essential for traffic safety and for reducing health risks in highly populated areas. More information can be found in Vukovic *et al.* (2014) and Dempsey (2014).

Table 5.2: Numerical models contributing to the WMO SDS-WAS (May 2016).

Model	Institution	Domain
BSC-DREAM8b_v2	Barcelona Supercomputing Center, Spain	Regional
CAMS	European center for Medium-Range Weather Forecast, U. K.	Global
DREAM-NMME-MACC	South east European Climate Change Center, Serbia	Regional
NMMB/BSC-Dust	Barcelona Supercomputing Center, Spain	Regional
MetUM	Met Office, U. K.	Global
GEOS-5	National Aeronautics and space Administration, U. S.	Global
NGAC	National Centers for Environmental Prediction, U. S.	Global
EMA REG CM4	Egyptian Meteorological Authority, Egypt	Regional
DREAMABOL	National Research Council, Italy	Regional
WRF-CHEM	National Observatory of Athens, Greece	Regional
SILAM	Finnish Meteorological Institute, Finland	Regional
CUACE/Dust	China Meteorological administration, China	Regional
MASINGAR	Japan Meteorological Agency, Japan	Global
ADAM	Korea Meteorological Administration, Korea	Regional

5.1 WMO Sand and Dust Storm Warning Advisory and Assessment System

Recognizing the importance for multiple societal sectors around the world to better understand and monitor atmospheric sand and dust, in 2007, the World Meteorological Organization (WMO) endorsed the launching of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). It has the mission to enhance the ability of countries to deliver timely and quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities (Terradellas *et al.* 2015).

The SDS-WAS works as an international, global network of research, operational centres and users, organized through regional nodes and coordinated by the SDS-WAS Steering Committee (WMO 2015). Three regional nodes are currently in operation: (i) Northern Africa, Middle East and Europe, (ii) Asia and Central Pacific, and (iii) Pan-America.

5.1.1 The SDS-WAS Regional node for Northern Africa, Middle East and Europe

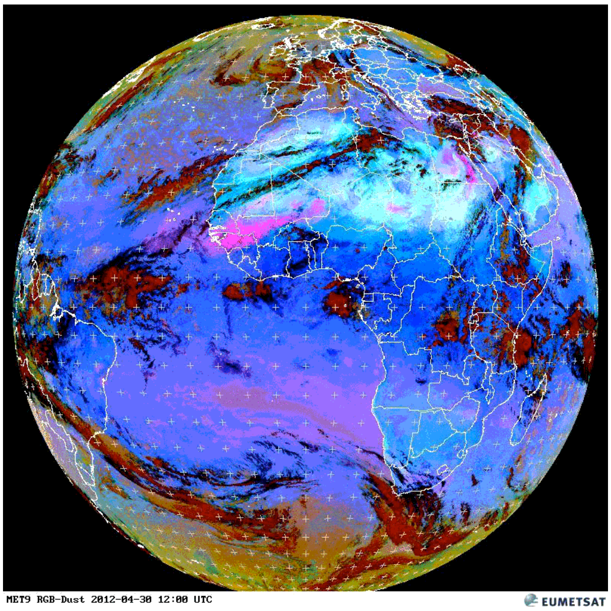
The node is coordinated by a Regional Centre (RC) set in Barcelona, Spain, hosted by the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Centre (BSC). The main objective of the Regional node is to facilitate user access, particularly for National Meteorological and Hydrological Services (NMHSs), to observational and forecast products as well as to other sources of basic information related to airborne dust. Its web portal (NA-ME-E 2016) provides users with the information needed to monitor dust events and to issue operational predictions and warning advisories related to the dust content in the atmosphere (Terradellas *et al.* 2014).

Observations and Monitoring Systems

The Meteosat Second Generation (MSG) dust product of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (Figure 5.1) is specifically designed to monitor the evolution of dust storms during both day and night. It is a Red-Green-Blue (RGB) composite based upon infrared channels of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiometer traveling on board the MSG satellites. The RGB combination exploits the difference in emissivity of dust and desert surfaces. In addition, during daytime, it exploits the temperature difference between the hot desert surface and the cooler dust cloud. The RGB composite is produced using the following MSG IR channels: IR12.0-IR10.8 (red), IR10.8-IR8.7 (green); and IR10.8 (blue). Dust appears pink or magenta (Figure 5.1). The temporal resolution and the quick availability of this product make it ideal for dust monitoring. The UK Met Office produces a quantitative retrieval of dust optical depth (DOD) over land from SEVIRI. It is based on empirical relationships between the radiance measured by the SEVIRI infrared channels and the DOD at 550 nm wavelength.

The Regional Centre web portal presents hourly images and 24-hour animations of both products, as well as online access to their archive. The web portal also provides access to hourly data from a selection of air quality monitoring stations. Most of these stations

Figure 5.1: The EUMETSAT RGB-dust product from 30 April 2012 at 12:00 shows a dust cloud extending from Central Sahara to the Eastern tropical Atlantic. Other dust clouds are visible in Chad, around the Bodélé depression and in Egypt.



have been selected for their rural location, away from important sources of anthropogenic pollution, as well as for their spatial representativeness (e.g., Figure 5.2). This information is complemented with back-trajectories, which allow investigating the origin of the air mass present over a particular site. They are computed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the National Oceanic and Atmospheric Administration of the US (NOAA).

The Regional Centre routinely produces 6-hourly plots indicating the stations, where the visibility has been reduced by sand or dust to less than 5 km. The plots are produced using METAR aeronautical meteorological reports (a standard format for reporting weather information) and surface synoptic observations (SYNOP) generated in synoptic meteorological bulletins from more than 1,500 stations. Brownish circles indicate stations where ‘sand’ or ‘dust’ has been explicitly reported, and triangles indicate stations where the present weather has been reported as ‘haze’, meaning that the visibility is reduced by particles of unspecified origin (Figure 5.3).

The Regional Centre conducts, in collaboration with WMO, the “Sand and Dust Storm Early Warning System in the Magreb Region” project (SDS-Africa), with the aim to reinforce the observational capacity for mineral dust in Northern Africa. The main goal of the project, financed by the Spanish Agency for International Development Cooperation, is to establish a ground-based network of sun-photometers in selected locations of Northern Africa for detecting and monitoring dust storms. They are also useful for

Figure 5.2: The record of particulate matter of 10 µm or less in diameter (PM10) and 2.5 µm in diameter (PM2.5) from Granadilla (Canary Islands, Spain), which clearly shows a major dust event on 25-26 December 2015 and a less significant one on 4-5 December. Source: SDS-WAS.

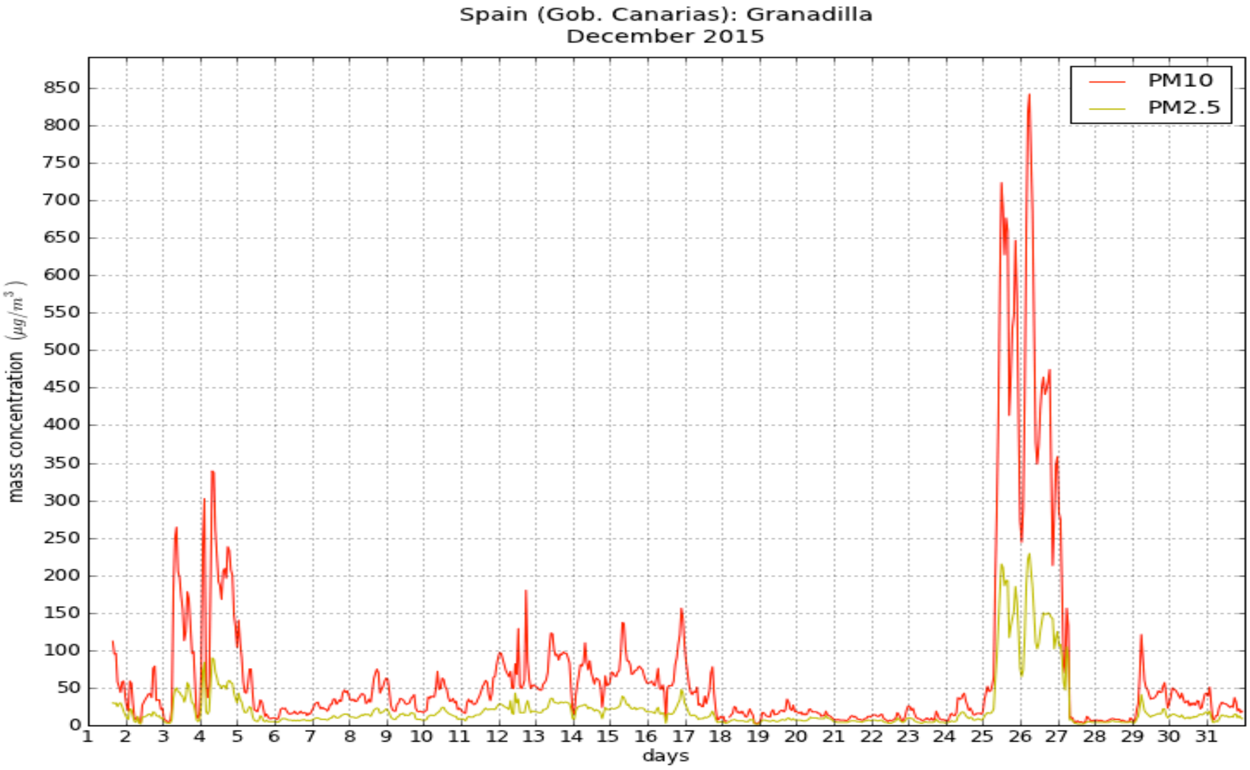
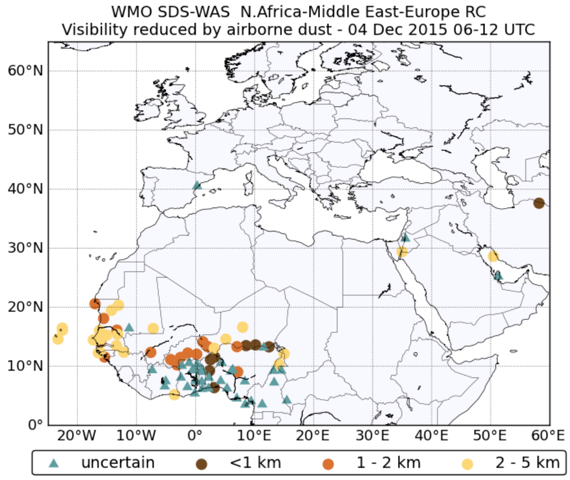


Figure 5.3: Visibility reduction by sand/dust on 4 December 2015 between 6 and 12 UTC. Source: SDS-WAS.



validating and calibrating satellite sensors, and for evaluation of dust models. Four stations are currently in operation and integrated in the AERONET network, namely: Ouarzazate (Morocco), Tamanrasset (Algeria), Tunis-Carthague (Tunisia), and Cairo (Egypt).

Forecasting

The exchange of forecast products is the basis for a model inter-comparison and joint evaluation. At the beginning of 2016, ten modelling groups provide daily files with numerical predictions of dust surface concentration (DSC) and dust optical depth (DOD) at 550 nm for a reference area extending from 25°W to 60°E longitude and from 0° to 65°N latitude. The action involves forecasts up to 72 h with a 3-hour frequency. The DSC and DOD provided by each model are plotted side-by-side daily for the reference area using a common colour palette. This product is a powerful tool to issue short-term predictions and early warning notices. Archived products are available online.

The Regional Centre also generates multi-model products (Figure 5.4) based on the exchanged forecasts. Products describing both centrality (multi-model median and mean) and spread (standard deviation and range of variation) are computed and posted on the web. In particular, the multi-model median is considered for the model inter-comparison and forecast evaluation. These products are also mirrored on UNEP Live (UNEP 2016).

A common evaluation protocol has been established in order to assess whether the modelling systems successfully simulate the temporal and spatial evolution of the dust-related parameters. For this purpose, sun-photometric observations from 40 dust-prone stations of the AERONET network are retrieved and plotted together with predictions for the same times and places on graphs. In addition to monthly plots, the evaluation system computes monthly, seasonal and annual scores. An evaluation product based on aerosol optical depth retrievals from MODIS has also been developed.

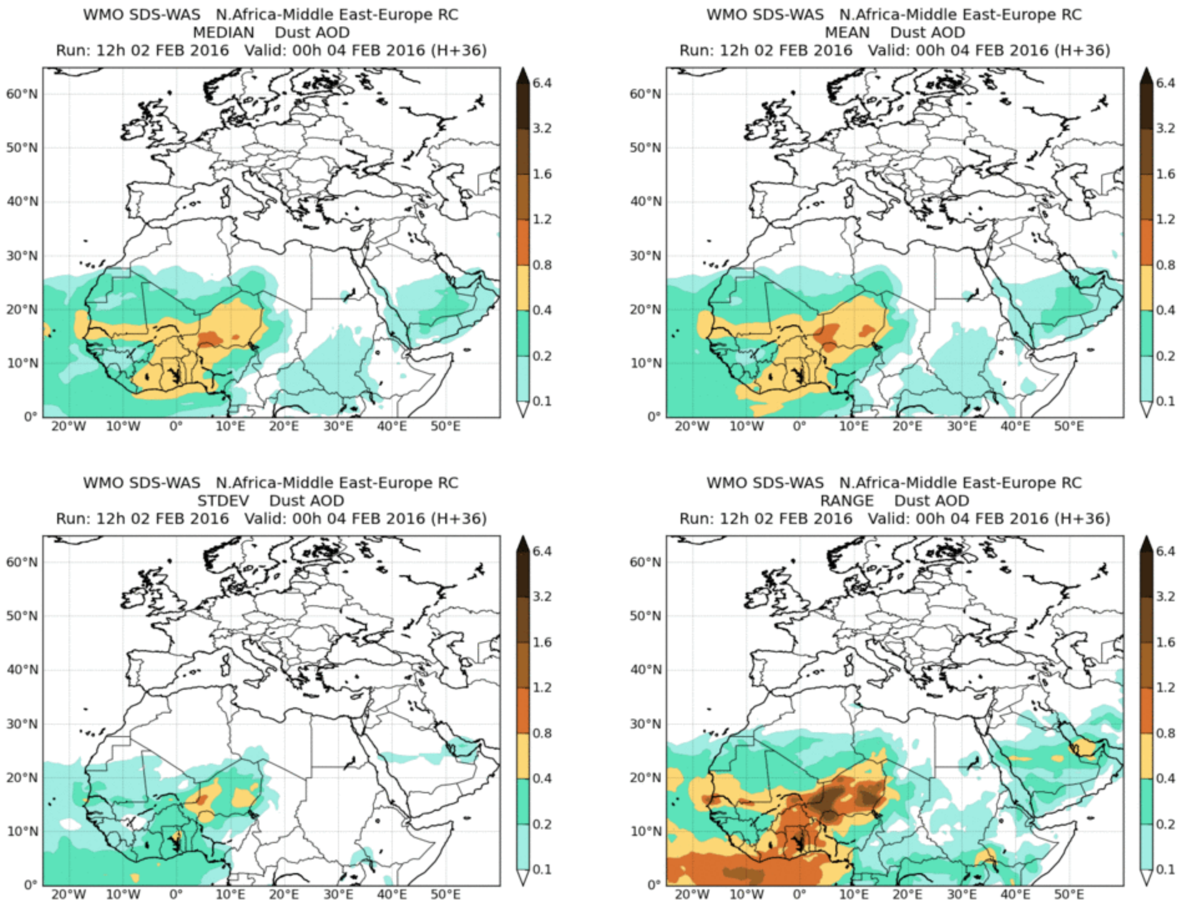
Capacity building

One of the basic objectives of the Regional Centre is to promote the use of dust-related products. For this purpose, the Centre coordinates, with partners and National Meteorological and Hydrological Services (NMHSs) in the region, different actions aimed at strengthening the capacity of countries to use the observational and forecast products distributed within the framework of the WMO SDS-WAS. A number of training events are organized by the Centre: during the past five years, eight courses and training workshops for SDS-WAS have been conducted in different countries and regions.

5.1.2 The SDS-WAS Regional node for Asia and Central Pacific

The Regional node is coordinated by a Regional Centre in Beijing, China, hosted by the China Meteorological Administration (CMA). The main objective of the Regional node is to support a global network of SDS-WAS research and operational partners, including the NMHSs of Japan, Kazakhstan, Mongolia, People's Republic of China, and Republic of Korea. It routinely runs one global and two regional models to provide dust forecast. The results of the different national forecasting systems – at present China, Korea and Japan – are shared on a web portal maintained by the Asia Regional Centre (2016).

Figure 5.4: SDS-WAS multi-model products valid for 5 February 2016 at 00 UTC.



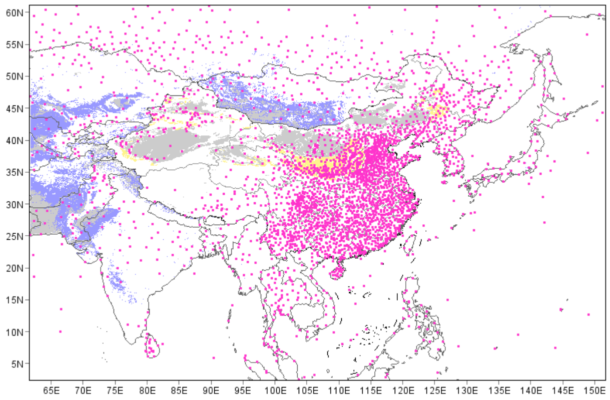
Observations and Monitoring Systems

Routine SDS Observation

The distribution of the weather stations in East Asia is shown in Figure 5.5. Most stations are located in the areas with high economic development. But in the SDS source areas, in the Gobi desert and sandy land areas, the distribution of the weather stations is very sparse. In the meteorological records, four categories of SDS events are usually reported in the daily observation: (i) suspended dust (horizontal visibility less than 10,000 m, and very low wind speed), (ii) blowing dust (visibility reduced to 1,000 – 10,000 m), (iii) sand and dust storm (visibility less than 1,000 m) and (iv) severe sand and dust storm (visibility less than 500 m). The last three categories of dust events all result from strong winds. Through a data transfer system, the near real-time SDS observation data with a 3-hour interval at these stations are obtained.

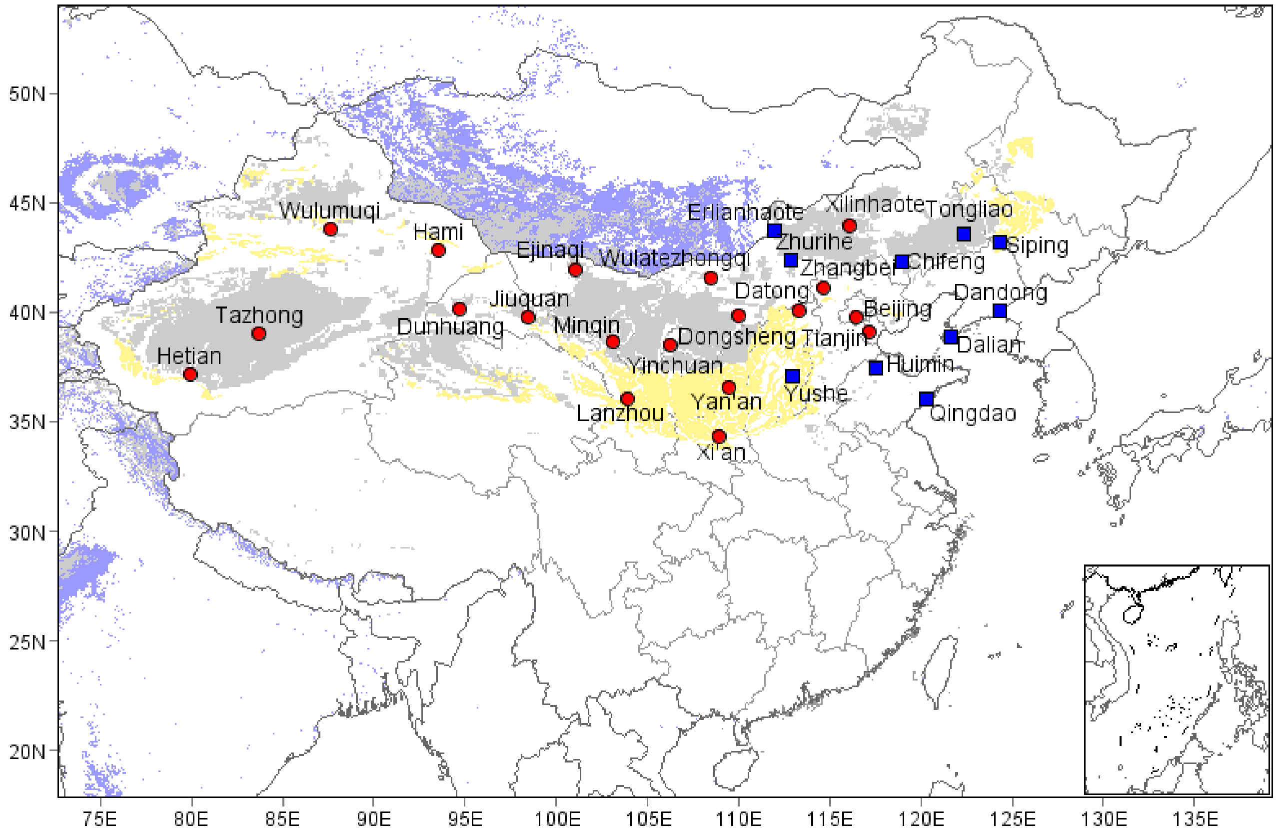
PM Mass Concentration

Figure 5.5: Routine meteorological observation stations in Asia and Central Pacific.



To obtain the dust particle concentrations during SDS events, the Meteorological Administrations of China (CMA), Japan (JMA) and Korea (KMA) have established PM monitoring networks that can be used for SDS verification. The CMA SDS monitoring network contains 29 stations located in or near SDS source regions in northern China (Figure 5.6), and 24 of them have monitored PM10 since 2003. Eleven of them are also equipped with instruments to measure visibility. At 19 of the stations Tapered Element Oscillating Microbalance (TEOM, model 1400a, Rupprecht and Patashnick) instruments operated at a controlled flow rate of 4 L/min were used to record continuously the PM10 mass concentrations averaged over five minute periods in each station. GRIMM

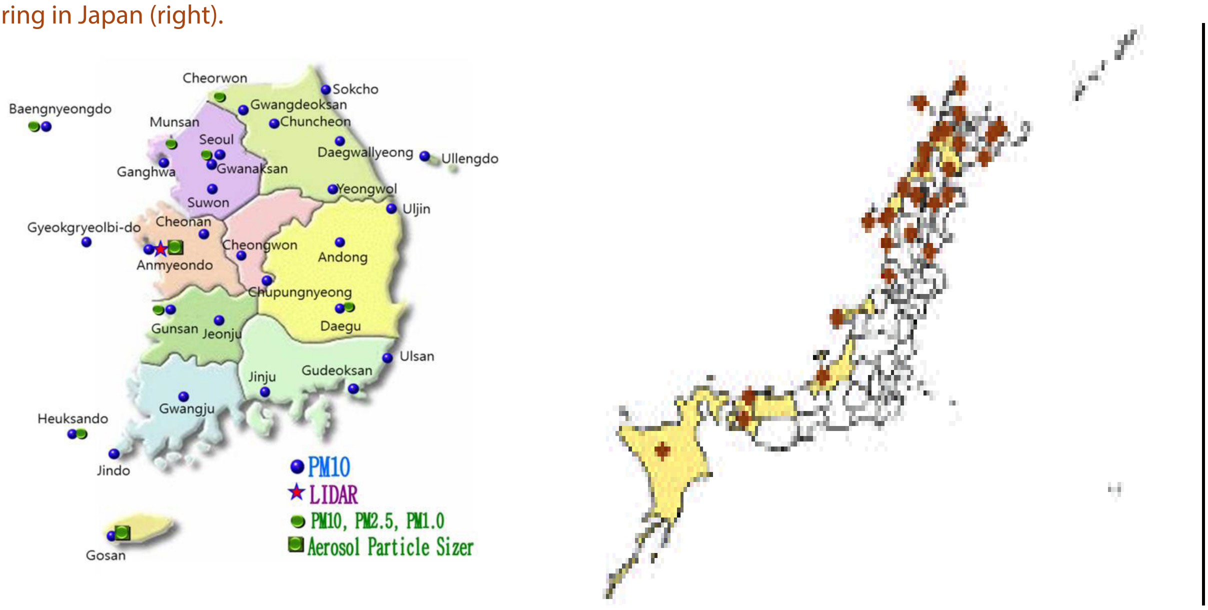
Figure 5.6: Sand and dust storm observation stations of China Meteorological Association, ten of them established from China-Korea cooperation (Blue colour).



instruments were used in the other five stations for PM10, PM2.5 and PM1 observation. At 11 of the stations 5-minute visibilities were also observed automatically on-line using an FD-12 visibility instrument (Vaisala). After experimental running of the SDS monitoring network in 2003, the PM10 and visibility observation data were gradually transferred to the CMA information centre in real-time from 2004.

Ten of the SDS stations have been established from the China-Korea cooperation (stations with blue colour in Figure 5.6). The observation data are shared between CMA and KMA at these stations. CMA also supported the establishment of three SDS stations (Underkhaan, Arvaikheer and Gobi-Altai) in Mongolia and one station (Kuygan) in Kazakhstan in 2009 and 2010, through bilateral cooperation.

Figure 5.7: Sand and dust storm observation stations of the Korean Meteorological Association (left) and PM10 monitoring in Japan (right).



There are 30 SDS observation stations in KMA located in South Korea (Figure 5.7). PM10 concentrations are monitored at all stations, meanwhile PM10, PM2.5 and PM1 data can be obtained at six of the stations. Aerosol vertical distribution data are observed at four of the stations. There is also a PM10 monitoring station network of the JMA for SDS and air quality observation (Figure 5.7).

Ground-Based AOD

The China Aerosol Research Network (CARSNET) is a ground-based network for monitoring aerosol optical properties (Figure 5.8), and it uses the same type of instruments as AERONET. CARSNET includes 20 sites located in north and northwest China that were first established by the CMA in 2002 for dust aerosol monitoring. This network has increased to more than 60 stations that are now operated not only by CMA but also by local meteorological administrations, institutes, and universities throughout China. This has become a national resource for studying aerosol optical properties over the different regions in China and for validating satellite retrievals and numerical models of aerosols.

Satellite Remote-sensing Data

An operational retrieval algorithm for SDS from FY-2C/2D satellites was developed by CMA (Hu et al. 2008). The Dust Retrieval Algorithm from Geostationary Imager (DRAGI) is based on the optical and radiative physical properties of SDS in mid-infrared and thermal infrared spectral regions as well as the observation of all bands in the geostationary imager, which include the Brightness Temperature Difference (BTD) in split window channels, Infrared Difference Dust Index (IDDI) and the ratio of middle infrared reflectance to visible reflectance. It also combines the visible and water vapour bands observation of the geostationary imager to identify the dust clouds from surface targets and meteorological clouds. The output product is validated by and related to other dust aerosol observations such as the synoptic weather reports, surface visibility, aerosol optical depth, and ground-based PM10 observations. Using the SDS-IDDI product and a data assimilation scheme, the dust forecast model CUACE/Dust achieved a substantial improvement in SDS prediction (Figure 5.9). Asian dust index products are also provided by the KMA Communication, Ocean and Meteorological Satellite (COMS) and the JMA Multifunctional Transport Satellites (MTSAT). (Figure 5.10).

Lidar Data

Lidars permit routine measurement of aerosol vertical profiles. However, continuous measurements in ground-based stations are only performed in a few stations that are, in general, far from the main dust sources, especially in JMA and other agencies of Japan (Figure 5.11).

Figure 5.8: CARSNET stations of China Meteorological Association with ground-based Aerosol Optical Depth (AOD) observation.

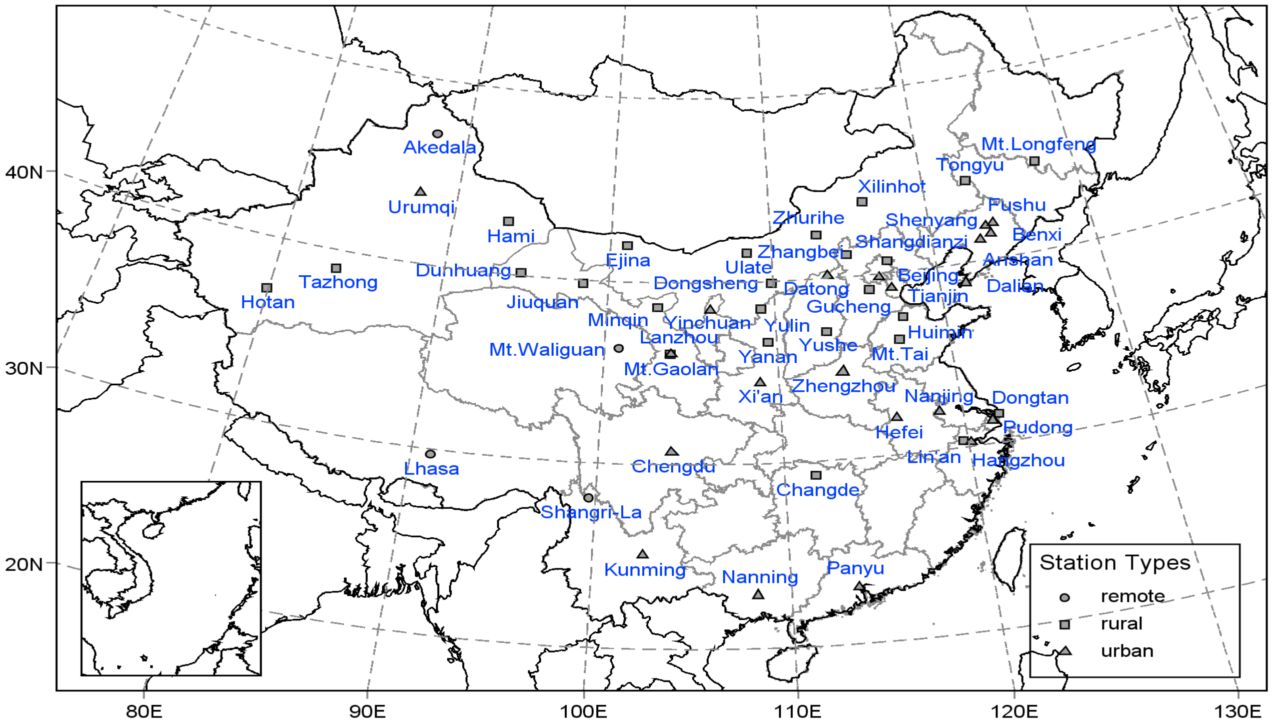


Figure 5.9: Infrared Difference Dust Index (IDDI) image from FY-2D satellite at 5:30 (UTC), March 30, 2007.

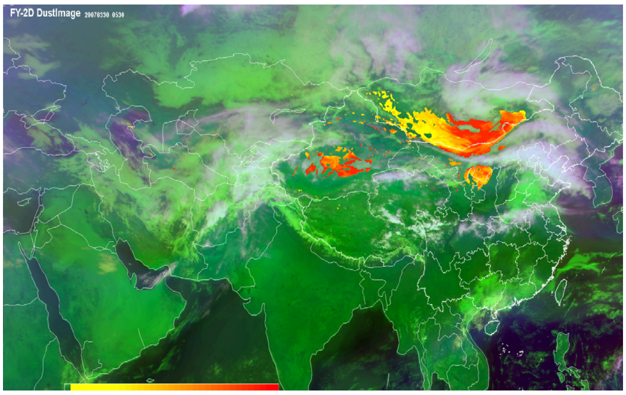


Figure 5.10: Asian dust index products provided by JMA MTSAT satellite

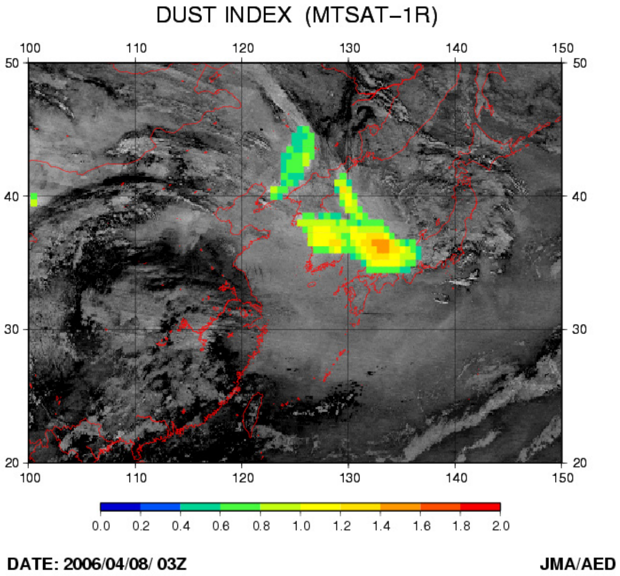
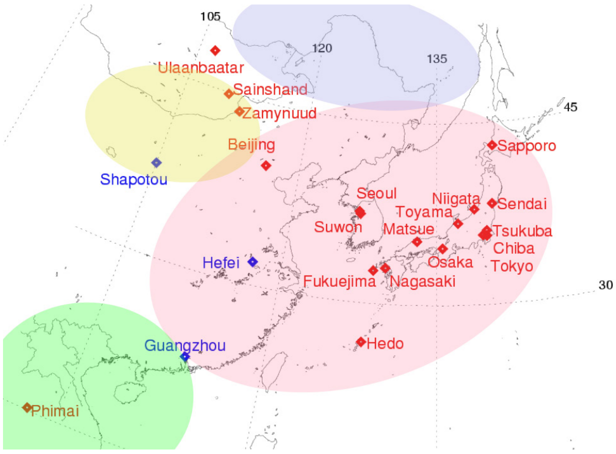


Figure 5.11: Lidar Network in East Asia.



Forecasting

Within the Asian node, there are one global (JMA) and two regional models (KMA and CMA) for running operational dust forecasts (Figure 5.12). The results of the different national forecasting systems – at present China, Korea and Japan – are shared on a web portal in the Asia Regional Centre (2016). At the same time, the SDS forecasts of the two global models, from ECMWF and NCEP, respectively, are also shown in the Regional Centre. A protocol for near real-time exchange of daily numerical forecasts for a joint visualization and evaluation has also been established at the Asia Regional Centre. The reference area covers the main dust sources in Central and Eastern Asia and transport routes and deposition zones up to the Central Pacific. Similarly to the Regional Centre for Northern Africa, Middle East and Europe, the initiative considers forecasts of surface concentration and dust optical depth with a 3-hour frequency up to a lead-time of 72 hours.

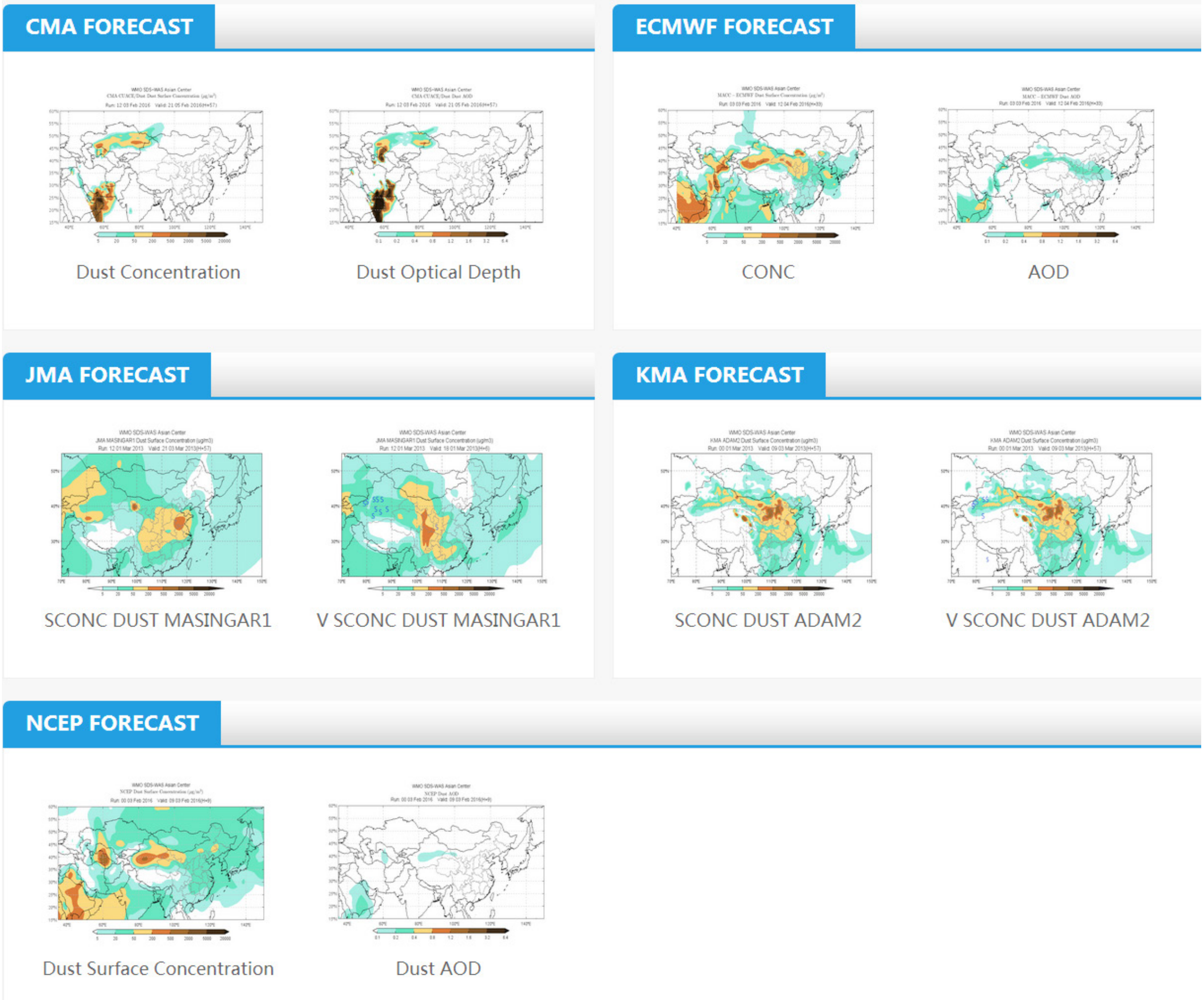
Capacity building

Basic objectives of the Regional Centre include to have better monitoring of SDS and to promote the use of dust-related products. For this purpose, the Centre coordinates actions with partners and NMHSs in the region that aims to strengthen the capacity of countries to use the observational and forecast products distributed by WMO SDS-WAS. Annual training workshops for operators of SDS data sharing stations of the Asia Regional Centre have been held in Seoul and Beijing.

5.1.3 The SDS-WAS Regional Node for Pan-America

The Regional Node is coordinated by a regional centre in Barbados that is hosted by the Caribbean Institute for Meteorology and Hydrology (CIMH). Following the aims of the SDS-WAS, the Pan-America Centre provides a focus and a node for collaboration across the Americas, working with other SDS-WAS centres to (i) develop, refine and distribute to the global community products that are useful in reducing the adverse impacts of SDS, and (ii) assess the impacts of SDS on society and nature. The Centre's highest priority is the great concern about airborne dust in the region and the adverse health implications. The region 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. The foremost objectives for 2016-2020 are to facilitate worldwide information exchange about the health consequences of windblown desert dust and to oversee launch and operation of a global Dust-Health Early Warning System (D-HEWS, see Section 5.4). Health concerns are paramount for the Americas, and the Caribbean

Figure 5.12: Sand and dust storm forecast for 3 February 2016 at 12:00 UTC issued by the Asia Regional Centre. Currently, SDS forecast results from the Japan Meteorological Association global model are not shared in real time with the Regional Centre. The Korea Meteorological Association regional model provides the forecast results during each Spring.



home of the Pan-America Centre has been a focus for study of Saharan dust measurements and ecosystem and human health consequences for over 50 years (Section 4.2). Information relevant to the Centre may be found on the CIMH web site (CIMH 2016).

Observations and Monitoring Systems

The Pan-America Centre works closely with and through NASA and other nations' space agencies. NASA almost exclusively supported the advances in synoptic dust forecasting pioneered through the Pan-America Centre (e.g., Luvall *et al.* 2011; Mahler *et al.* 2006; Sprigg *et al.* 2008; Sprigg *et al.* 2014; Vukovic *et al.* 2014; Yin and Sprigg 2010; Yin *et al.* 2007ab). Satellite based observations to detect, define and monitor dust sources are essential for forecasting and simulating emissions in atmospheric dust models. Space-based instruments operated by national space agencies provide unique measures of airborne dust, their three-dimensional characteristics, and their paths along global air currents.

As part of the process to coordinate observations and networks, the Centre is examining a new initiative for an aerosol air quality program in the Caribbean project to *Reduce Risks to Human and Natural Assets Resulting from Climate Change (RRACC)*, based in St. Lucia. The Centre also encouraged and participated in the 2015 *Symposium on Airborne Dust, Climate Change & Human Health* (University of Miami, 19-21 May 2015) and collaborated in the *Symposium Celebrating 50 Years of Sahara Dust Research on Barbados* (hosted by the Caribbean Institute for Meteorology and Hydrology, CIMH, 16-17 October 2015). Both symposia presented an opportunity to review and assess the ground-based observational networks essential to document, and through modelling predict, airborne dust extent in the region. The 2015 *Symposium Celebrating 50 Years of Sahara Dust Research on Barbados* reaffirmed links and dependencies with ground-based networks in the Caribbean and beyond. Reports from these symposia are in preparation, but the Centre's partners continue to rely on international networks of AERONET (Aerosol Robotic Network) and MPLNET (Micro Pulse Lidar Network) for upward-looking profiles of airborne dust. These observations, along with ground-based measurements of PM10 and PM2.5, are critical to model verification and documentation of particulate air quality.

Pan-America Centre teams are being formed to assess needs and identify the means for both MPLNET and the assembly of PM in-situ observation networks to deliver the best possible information for SDS-WAS dust forecasting and the Dust-Health Early Warning System. The formation of these teams is an example of the role of the Pan-America Centre Science Steering Group. Guidance from the 2015 Symposium in Barbados recommends a study team, that includes representatives of NASA and Germany's Max Planck Institute for Meteorology, to draft a plan and proposal to expand MPLNET in order to fill information gaps in the Pan-America region and to improve the global aerosol monitoring program that supports SDS-WAS dust model forecasts, simulations and verification.

A second team from the Pan-America Centre is preparing a plan to back an appeal for funds to continue and sustain the 50 years of observations from Ragged Point, the most eastward point on Barbados (see, for example, Prospero *et al.* 2014). To begin, the team will examine the justification and the means for networking with other ground-based aerosol networks in the region and around the world. Observations from Ragged Point would, for example, be part of a current air quality observation initiative of the Organization of Eastern Caribbean States (OECS), comprising Antigua and Barbuda, the Commonwealth of Dominica, Grenada, Montserrat, St. Kitts and Nevis, St. Lucia, St. Vincent, and the Grenadines. Anguilla and the British Virgin Islands are associate members of the OECS. The CIMH, home of the Pan-America Centre, is offering PM measuring instruments for the OECS initiative. The Centre will coordinate observations from this network with others in the region, including the US Environmental Protection Agency's AIRNow network, the University of California Davis campus IMPROVE (Interagency Monitoring of Protected Visual Environments) network, Environment Canada's National Air Pollution Surveillance Network, and ground based networks in the French Caribbean and Puerto Rico.

A recent sign of the seriousness in which airborne dust is taken in the Caribbean is the formation of a Caribbean Aerosol-Health Network (CAHN). The CAHN objective is to improve understanding of the broad consequences (e.g., climate, weather, ecosystems, air quality, energy, visibility, and health) of atmospheric particulate matter in the Caribbean region. The group behind the CAHN includes several of the stakeholders and institutions mentioned previously, all with an agreed upon aim of coordinated international efforts to measure PM across the Caribbean, including a particular interest in dust from Africa. The variety of potential consequences of airborne dust, and the many occupations necessary to understand and respond to them, is a transdisciplinary challenge for the institutions involved.

Coordination and expansion of these networks, especially the measurements they take, would allow faster recognition of the linkages between airborne dust and human health and the consequent reduction of health risks. This is particularly true of a lack of observations that speciate, or break down, the composition of dust plumes and particles. As medical research focuses on the specific biological, mineral and chemical elements that injure bodily tissue and function, observations of the speciated composition of in-situ airborne dust must keep pace. And, as the following discussion will show, observations must keep pace with modelling. Models that now forecast and simulate downwind mineral fractions (Nickovic *et al.* 2012; Nickovic *et al.* 2013) need the in-situ observations for model verification.

Forecasting

The Pan-America Centre exploits the long-standing working relationships with all Caribbean weather services through the CIMH (2016). The US National Weather Service participates in the plans and programmes of the Centre. The head of CIMH represents the interests of Caribbean weather services at WMO. An objective of all these entities is accurate and timely forecasts of windblown dust for reasons of health and safety, improved weather forecasts and better understanding of climate processes.

Partners in the Pan-America Centre include researchers in universities across the United States and in government laboratories and operational centres of NASA, the National Weather Service (NWS), the Navy, the Environmental Protection Agency (EPA), the Centres for Disease Control and Prevention (CDC), and the Departments of Agriculture and Interior. Each one contributes to dust forecast development. The CDC samples soils and airborne dust for harmful substances that are transported with the dust (such as the mould spores that cause Valley fever in the Pan-America sector) from the Western US through Mexico and into Central and South America. Some agencies provide several important contributions, for example the NWS, EPA and Navy provide observations, models and missions that help set goals for model forecasts and simulations. NASA supported the DREAM dust model at the University of Arizona to simulate pollen plume transport and dispersal (Luvall *et al.* 2011). The USDA and Department of Interior work on dust and questions of airborne pollen, black carbon, wildfire smoke, volcanic ash and soil erosion. The historical activities of CIMH show long-term collaboration on aerosols with the Max Planck (Hamburg) Institute of Atmospheric Physics (Munich) and the Leibniz Institute for Tropospheric Research (Munich).

The Centre relies on its partnership with laboratories and services of many US agencies for state-of-the-science dust modelling, including: the US Naval Research Laboratory (NRL) in Monterey, California; the EPA in Research Triangle Park, North Carolina; the University of California Los Angeles and Irvine campuses; the Desert Research Institute in Reno, Nevada; the University of Arizona in Tucson; and the National Oceanic and Atmospheric Administration (NOAA). NOAA laboratories develop operational dust weather and climate information products for the US National Weather Service. This resource is available directly from NOAA and will be available soon through the Pan-America Centre. These operational products and the CIMH dust forecasts of transport of Africa dust plumes to the Caribbean region, in collaboration with the SDS-WAS Centre in Barcelona, are the only operational dust model products currently available through the Pan-America Centre.

The Centre proposes to restart operation of the Dust Regional Atmospheric Model (DREAM/NMM - a dust storm simulation model to simulate spore emission, transport and deposition) over the US Southwest and northern Mexico (Sprigg *et al.* 2014; Sprigg 2016), principally for Valley fever, asthma and cardiovascular epidemiology, and risk avoidance. A next step for the Caribbean would integrate and downscale DREAM/NMM with the Africa dust plume forecasts to achieve high spatial resolution (<3 km) dust forecasts across the Caribbean, including Trinidad and the northern reaches of South America, to Florida and west into Central America.

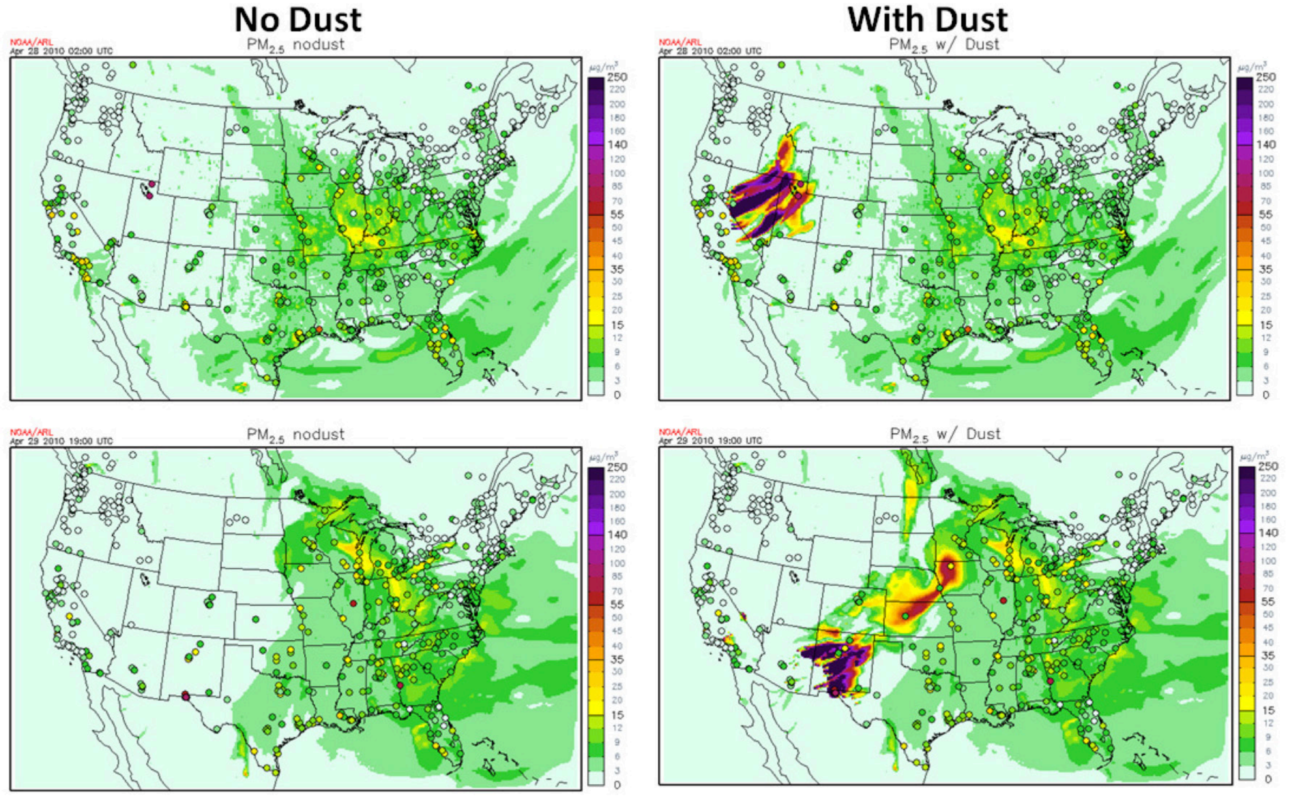
Considering the vital role of windblown dust in marine primary productivity, and the public health and economic value of marine fisheries in the Caribbean, the next step for DREAM operations from the Centre will incorporate particle differentiation, particularly iron and phosphates, which are the key mineral deposits for marine life. Iron, too, is an important factor for human health.

NOAA Dust Observations and Forecasting

NOAA's National Air Quality Forecast Capability (NAQFC) (Pan *et al.* 2014; Tong *et al.* 2014) is accessible to all. It provides real-time numerical guidance of air quality to the continental United States, Hawaii and Alaska (NWS 2016). NAQFC forecasts ozone, PM2.5 dust, and wildfire smoke. The dust emission module for the NAQFC Community Multi-scale Air Quality (CMAQ) is a semi-empirical dust emission scheme that incorporates land and soil-specific threshold friction velocities determined from wind tunnel and field experiments (Gillette and Passi 1988; Gillette *et al.* 1980). The threshold friction velocities are further modified by surface conditions, including surface roughness, soil moisture, rainfall, and snow/ice cover. The FENGSHA source code (Tong *et al.* 2008) is available with CMAQ version 5.0 by the US Environmental Protection Agency (CMAQ 2016). Currently, NOAA's Air Resources Laboratory integrates FENGSHA (a physical-based dust emission algorithm) into the HYSPLIT forecasting system to provide dust emission input to the HYSPLIT for dust transport and removal. Initial application of FENGSHA over the continental US showed promising results by capturing dust storms of various magnitudes (Figure 5.13). The integration of FENGSHA with the HYSPLIT atmospheric transport and dispersion model allows the assimilation of several satellite products to replace model-predicted parameterization of the surface conditions.

Long-term dust climatology over the western United States demonstrates how surface dust observations are important to evaluate dust forecast models to produce one set of useful dust mitigation and risk assessment products. Tong *et al.* (2012) have developed and make available a long-term surface dust database in the western United States. By careful analysis of NASA Earth Observatory's Natural Hazards dust product, a dataset of US-originated dust storms was obtained. Based on this dataset, aerosol data from the IMPROVE (Interagency Monitoring of Protected Visual Environments) network that match the time and location of these dust storms are selected to extract distinct properties of local dust samples. Comparison of the size distribution and chemical composition of the IMPROVE aerosol data before, during and after dust storms shows a few persistent patterns. Based on the observations above, Tong *et al.* (2012) proposed five dust indicators to be used to identify local dust storms: (i) high PM2.5

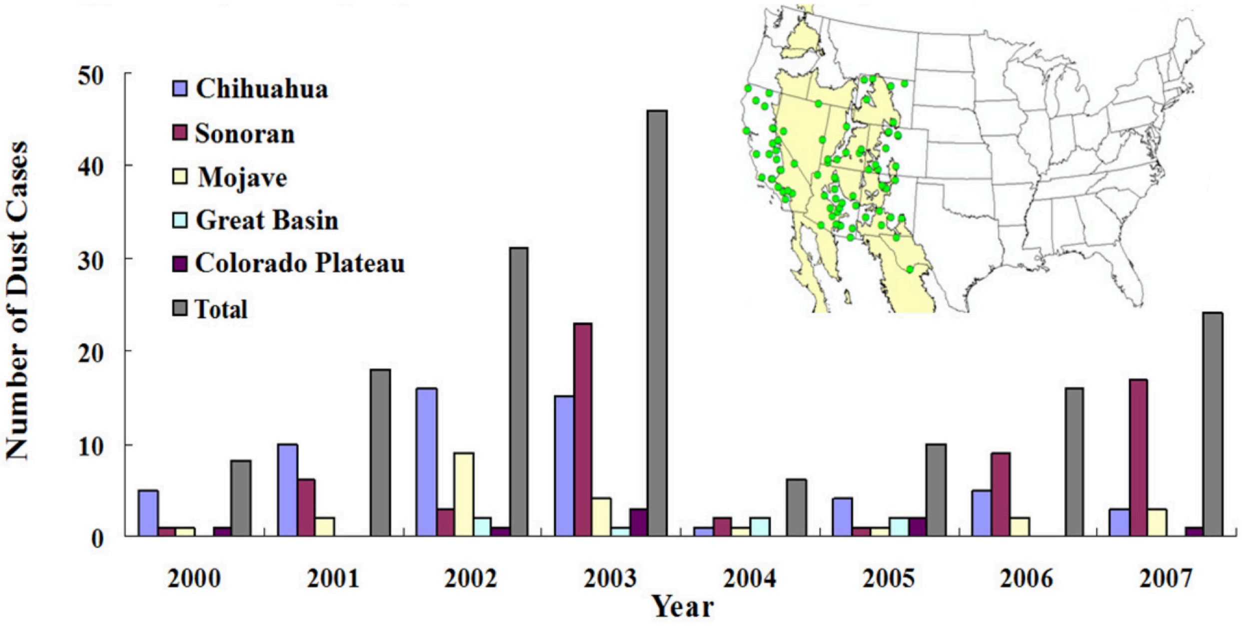
Figure 5.13: Comparisons of the PM2.5 forecasting over the United States with (left) and without (right) FENGSHA dust emissions for two major dust storms in the Great Basin Desert and the Chihuahua Desert, respectively.



concentrations, (ii) low ratio of PM2.5 to PM10, (iii) high concentrations and percentage of crustal elements, (iv) low anthropogenic pollutants, and (v) low enrichment factors of anthropogenic elements.

Additional, useful information can be gleaned from these observations and this approach. For example, Tong *et al.* (2012) identified a total of 182 local dust events over 30 Southwestern locations from 2000 and 2007 (Figure 5.14). During the eight-year study period, the total number of dust events displays an interesting four-year activity cycle (one in 2000-2003 and the other in 2004-2007). The years of 2003, 2002 and 2007 are the three most active dust periods, with 46, 31 and 24 recorded dust events, respectively, while the years of 2000, 2004 and 2005 are the

Figure 5.14: The annual frequency of local dust cases from 2000 to 2007 in the five dust source regions, namely, the Chihuahuan Desert, the Sonoran Desert, the Mojave Desert, the Great Basin Desert and the Colorado Plateau. Modified from Tong *et al.* (2012).



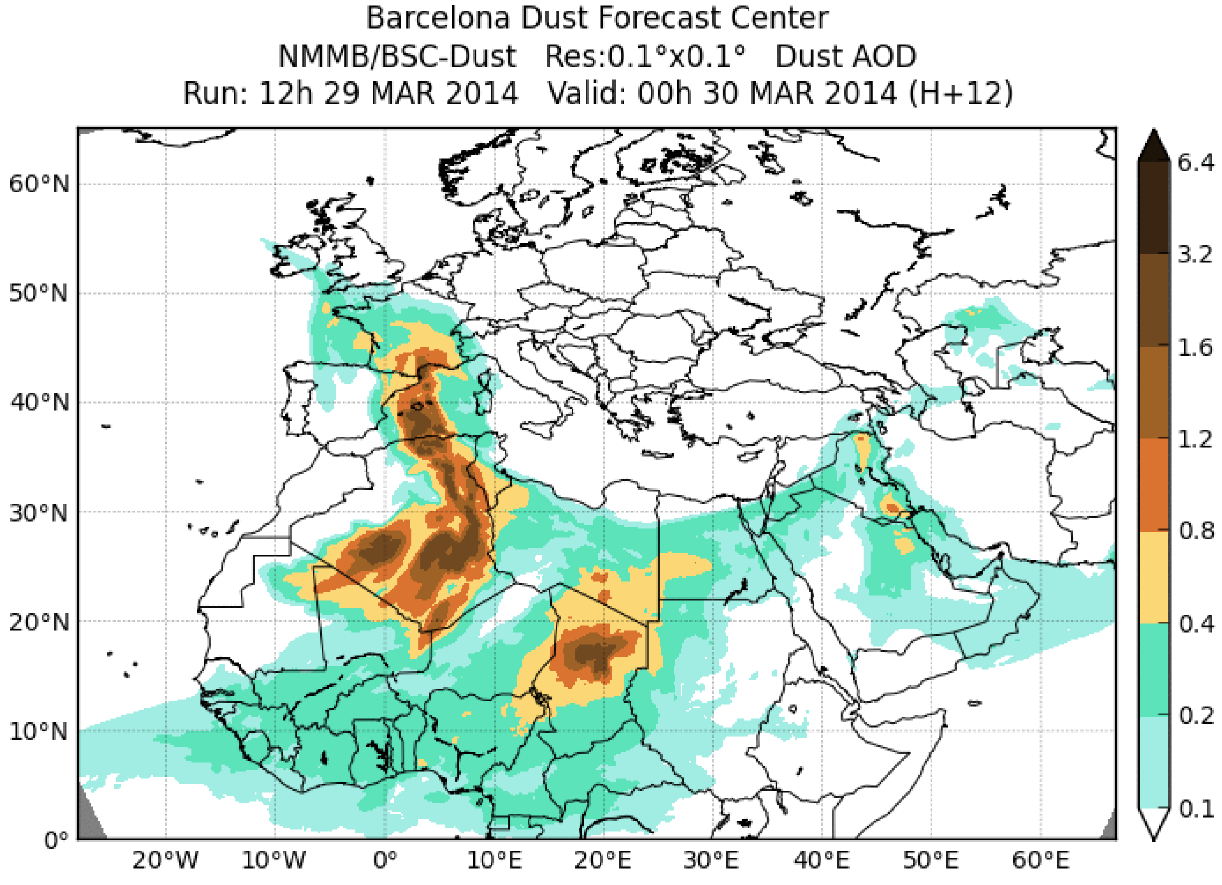
calmest periods, all with less than 10 cases. Among the deserts, the Chihuahuan Desert (59 cases) and the Sonoran Desert (62 cases) are by far the most active source regions. In general, the Chihuahuan Desert dominates dust activities in the first half of the eight-year period while the Sonoran Desert in the second half.

Training and Technology Transfer

The CIMH conducts an ongoing, twice-yearly *Caribbean Climate Outlook Forum* (CariCOF), which is a conduit for information and a base for training in airborne dust related issues (CRCC 2016). The proposed *Dust-Health Early Warning System* will supply dust forecasts, alerts and warnings for air quality and health service organizations, such as the US Environmental Protection Agency (EPA), the US Centres for Disease Control and Prevention (CDC) and the Caribbean Public Health Agency (CARPHA). Dust simulations from the entire network of SDS-WAS will be provided for epidemiology, ecology, climate and weather research, and trans-disciplinary historical case studies.

The CIMH is a *WMO Regional Training Centre*, a resource available to the Pan-America Centre and the SDS-WAS. The CariCOF, a feature of the Training Centre, will be adapted to meet priorities of the Pan-America Centre. Personnel from regional Meteorological Services and other stakeholders and entities are sent to complete courses at various levels including degree level at the University of the West Indies Cave Hill campus. There are continuing professional development courses offered (both online and through face to face instruction). CariCOF also update and deliver monthly climate outlooks and weather forecasts to a range of regional and national stakeholders. A drought alert system is included, which was developed with stakeholders. The ongoing CariCOF will assimilate dust-related training, including modelling, observations and applications in health, ecology, weather and climate. Training in uses and applications of products from forecasts and simulations, and dust and aerosol monitoring, are in preparation and are to be part of current ongoing courses and/or incorporated into special courses or continuing professional development modules. Other products and applications will be added as training continues for dust warnings across the region. A biennial Dust Storm Diagnostics Workshop is proposed that will bring forecasters and empirical and theoretical scientists together to assess progress in understanding and predicting dust storms and

Figure 5.15: H+12 forecast of dust optical depth at 550 nm released by the Barcelona Dust forecast Centre on 29 March 2014 at 12 UTC. Source: Barcelona Dust Forecast Center.



downwind concentrations, and to encourage pathways for collaboration and information and technology transfer.

5.1.4 Barcelona Dust Forecast Centre

In order to develop the operational component of SDS-WAS and to transfer the experience gained in the research phase to the operational services, the Barcelona Dust Forecast Centre was opened in February 2014, following the WMO decision that dust prediction was mature enough to implement operational services. AEMET and the Barcelona Supercomputing Centre (BSC) host this WMO Regional Specialized Meteorological Centre for Atmospheric Sand and Dust Forecasts (RSMC-ASDF) with the mission to generate and disseminate operational predictions for Northern Africa (north of the equator), Middle East and Europe.

The forecast fields (Figure 5.15) are generated using the NMMB/BSC-Dust model (an online multi-scale atmospheric dust model developed at the Barcelona Supercomputing Centre) run at a horizontal resolution of 0.1 degrees and distributed through the centre web portal (BDFC 2016; Pérez Garcia Pando *et al.* 2011). This distribution is through the WMO Global Telecommunications System and through EUMETCast, which is a dissemination system managed by EUMETSAT based on standard digital video broadcast technology. This uses commercial telecommunication geostationary satellites to multi-cast files (data and products) to a wide user community.

5.2 Copernicus Atmosphere Monitoring Service (CAMS)

The Copernicus Atmosphere Monitoring Service (CAMS) is the European Union's Earth observation programme and provides operational information services. Its aim is to equip society, business and industry, and policy-makers with tools and data to understand and adapt to a changing environment, whether that be related to economics, resilience or climate.

Some of today's most important environmental concerns relate to the composition of the atmosphere. The increasing concentration of the greenhouse gases and the effect of aerosols are prominent drivers of a changing climate. At the Earth's surface, aerosols, ozone and other reactive gases such as nitrogen dioxide determine the quality of the air around us, affecting human health and life expectancy, and the health of ecosystems. Ozone distributions in the stratosphere influence the amount of ultraviolet radiation reaching the surface. Dust, sand, smoke and volcanic aerosols affect the safe operation of transport systems, the availability of power from solar generation, the formation of clouds and rainfall, and remote sensing by satellite of land, ocean and atmosphere. CAMS has been developed to address these concerns by providing information on atmospheric composition though modelling and assimilation to those that need it. All data from CAMS are freely available to the public.

Specifically, the dust forecast activities in CAMS have been developed over a number of years under different EU-funded projects such as the Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data (GEMS) and Monitoring Atmospheric Composition and Climate (MACC) projects. The first forecast from an aerosol analysis was issued in 2008 and it provided the 4-day synopsis of global aerosols including desert dust, sea salt, sulphate, organic matter, and black carbon. Since then the system has undergone several refinements, particularly for dust aerosols via improved source description and parameterizations. Currently, the system assimilates Aerosol Optical Depth at 550 nm from the Moderate Resolution Imaging Spectroradiometer, flown on two NASA spacecraft (Terra and Aqua) to provide the aerosol initialization.

The assimilation is performed with the four dimensional variational (4D-Var) system operationally used for weather forecasts at the European Centre for Medium-Range Weather Forecasts (ECMWF). The aerosol physical routines are embedded in the ECMWF's Integrated Forecast System (IFS). The version of IFS which is run with chemistry and aerosols is called Composition IFS (C-IFS). Several other chemical species are modelled and assimilated in the system. The global modelling system is used for global forecasts and also to provide the boundary conditions for an ensemble of regional models that produce 4-day forecasts of air quality for Europe.

Dust forecasts from the CAMS system are downloaded daily by users. They are also contributed to the WMO SDS-WAS system as well as to the International Community for Aerosol Prediction (ICAP) multi-model ensemble systems.

5.3 International Cooperative for Aerosol Prediction (ICAP)

The development of data assimilation methodologies and near-real-time forecasting systems for aerosol applications have significantly accelerated in the last decade. This has happened in parallel with the increasing availability of aerosol observations available from Earth Observation Systems and other satellite measurements. In recognition of the growing number of operational aerosol models, and the desire to develop shared practices and compatible aerosol forecast products for both research and applications, the International Cooperative for Aerosol Prediction was created as a forum to exchange experiences and share creative solutions to common problems.

ICAP (ICAP 2016; Colarco *et al.* 2014) was established after two initial meetings that took place in Monterey in Spring 2010 and in Oxford in Autumn 2010. Those meetings are documented in Reid *et al.* 2011 and Benedetti *et al.* 2011. Since then, several other meetings have taken place. The focus has varied from aerosol observability and verification to source/sink processes, ensemble modelling, and assimilation. Participating centres are the Naval Research (NRL) Laboratory with the Navy Aerosol Analysis and Prediction System (NAAPS); the NASA Global Modeling and Assimilation Office (GMAO) with the Goddard Earth Observing System, Version 5 (GEOS-5) model; the Japan Meteorological Agency (JMA) with the Model of Aerosol Species IN the Global AtmospheRe (MASINGAR); the Barcelona Supercomputing Centre (BSC) in Spain with the Non-hydrostatic Multiscale Model (NMMB)-BSC Dust model; the U.K. Meteorological Office (UKMO) with the Unified Model; and ECMWF with C-IFS and the National Centre for Environmental Prediction (NCEP) with the Goddard Chemistry Aerosol Radiation (GOCART) model online with their Global Forecast System (GFS). More details on the ICAP models can be found in Benedetti *et al.* 2014.

The most significant accomplishment of ICAP has been an agreement between the various modelling centres to share their products (internally at first) on a common website so that they could be easily compared. This has led to the development of a web-based multi-model ensemble for dust forecast, conceptually similar to WMO SDS-WAS but with global rather than regional focus. Most models participating in ICAP also contribute to the WMO-SDS activities. Due to the global nature of the ICAP forecasts, dust forecasts can be provided for all the nodes of WMO-SDS. Dust was the focus of the initial effort which now extends to other aerosol species, due to the fact that most centres started aerosol forecasting activities around dust, which was recognized as one of the most important aerosol species for air quality, weather and climate applications. The ICAP multi-model ensemble forecasts have been shown to perform better than any single participating model (Session *et al.* 2015), illustrating the benefit of an ensemble approach to dust forecasting.

Ultimately, aerosol forecasting will likely emulate the developments achieved in Numerical Weather Prediction, and ICAP is positioning itself to take advantage of the best practices from that community. The continuing dialogue with satellite data developers and providers will remain crucial for providing innovative, timely, and freely available aerosol data products. Given aerosol forecasting's roots in the climate community, ICAP will continue to serve as a bridge between climate science and operational predictions.

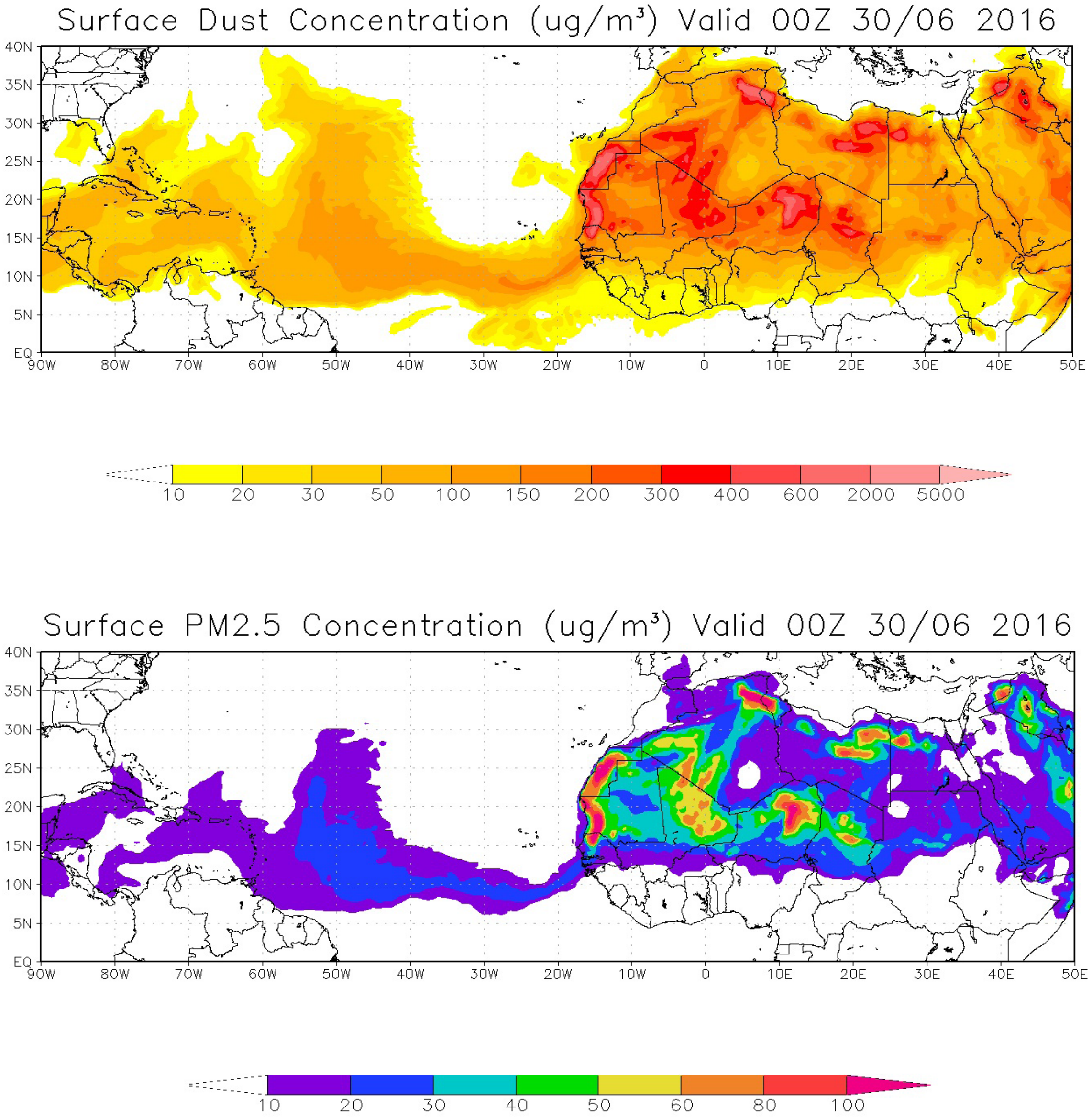
5.4 A Global Dust-Health Early Warning System

Airborne mineral dusts, and whatever biological and chemical elements that hitchhike with them, affect not only the health of the people who live within the prime source regions, but the health of their neighbours and people a continent or ocean away as well (e.g., Kanatani *et al.* 2010). The surest way to reduce these health consequences is to avoid inhaling the dust, which calls for a timely system to warn vulnerable populations of approaching dust plumes.

Today dust sources can be identified and monitored from satellites for emission characteristics. Composition of the soil sources, including mineral, chemical and biological data, is being compiled worldwide (e.g., Nickovic *et al.* 2012), albeit slowly and unevenly. Dust plumes, shaped by the wind, may be tracked by satellite and verified by lidars, and their deposits measured in air quality networks around the world, many of which collaborate with UNEP for a global perspective (UNEP 2015a). The SDS-WAS monitors and applies technological advances, the data from them, and accumulated understanding to advance dust forecast capabilities in the broadest sense. For example, distinctions are made between mineral components and size distributions, which are important distinctions in ascribing potential health risks. This is the first component of a global Dust-Health Early Warning System (D-HEWS), as an extension of the SDS-WAS programme.

Other principal components of D-HEWS include ones that are aimed at those who would interpret and distribute the warnings from SDS-WAS and those who would receive them, the beneficiaries. Since health risks vary across locations and communities (the "beneficiaries"), a network of weather and public health services is necessary to effect measurable reductions in health risks. Public and private weather

Figure 5.16: Seven-day forecast of (a) near surface dust concentration and (b) surface PM2.5 concentration forecast valid for 00Z, June 30 2016. Source: CIMH (2016).

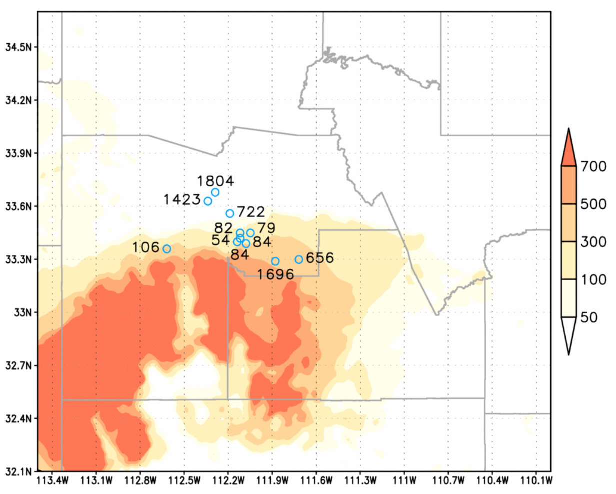


services benefitting from WMO coordination of national weather resources, working with the SDS-WAS, provide one such network, passing dust-specific forecasts and information on current conditions on to the international, regional and local health agencies that translate and disseminate health alerts to affected communities. This network tailors information to people and place, and is most effective when there is a collaboration among weather and health agencies and social and news information outlets.

Two categories of D-HEWS warnings from the perspective of SDS-WAS objectives are described in Sprigg (2016), where precepts for the D-HEWS are developed further. An example of the first category is medium-range forecasts and tracking of dust plumes off the Sahara Desert that affect air quality, asthma and other respiratory and cardiovascular complications from Barbados to Florida and westward (e.g., Molinie 2015). Pioneers in this case include Prospero and Mayol-Bracero (2013) and collaborators in the SDS-WAS Africa, Middle-East Centre, as reported in Knippertz and Todd (2011) and Perez Garcia-Pando *et al.* (2014). Figure 5.16 is an example from the web pages of the CIMH in collaboration with the SDS-WAS Centre in Barcelona.

Because meningitis epidemics in the Sahel, which occur in the latter part of the dry season, are highly correlated with dusty weather, WHO, WMO and other global partners formed the Meningitis Environmental Risk Information Technologies (MERIT) project (Thomson *et al.* 2013) to test whether epidemics can be predicted and if early warnings are effective. Dust

Figure 5.17: NMME DREAM 16 hour hindcast of a 5 July 2011 haboob through Phoenix, Arizona, USA. PM10 near surface concentrations (µg m^{-3}); spatial resolution ~ 3.5 km. Source: Vukovic *et al.* (2014); Sprigg *et al.* (2014).



forecasts (Pérez García-Pando *et al.* 2014), including mineralogy (Nickovic and Perez 2009), are being applied along with other models.

The second warning category is a mesoscale, 24- or 36-hour forecast of near surface PM2.5 or PM10 concentration at spatial scales of less than 4 km, exemplified by the DREAM/NMM Phoenix, Arizona, haboob forecast in July 2011 (Figure 5.17; Vukovic *et al.* 2014) and regional airborne dust model simulations for Valley fever epidemiology in the southwest United States (Sprigg *et al.* 2014).

Finally, under conditions of climate change (IPCC 2014a), deserts and the world's sources of airborne dust will change as well. This will change health risks and the strategies and efforts needed to survive them. Early warning systems for health in a changing climate are promoted in a 55-page report of the *Lancet* Commission on Health and Climate Change (Watts 2015). The D-HEWS and the SDS-WAS early warnings of unacceptable levels of airborne dust will be put to good use.

6. Technical Measures for Mitigating SDS

In this section, technical measures for mitigating SDS are reviewed, separated according to control measures in: (i) natural ecosystems and rangelands, with a focus on preventive measures, (ii) crop lands, (iii) industrial settings, including mining and (iv) urban areas and for protection of infrastructure. Finally the different measures are combined into an integrated approach to landscape management for SDS mitigation. Control measures in rangelands and crop lands are relevant to reducing wind erosion in general and not only to mitigating SDS. Measures in natural ecosystems and for protection of urban areas and infrastructure include those aimed at controlling windblown sand and moving sand dunes, which can occur at wind speeds below those required to generate SDS.

6.1 Control measures in natural ecosystems and rangelands

In natural ecosystems and rangelands, preventive measures are key to preventing soil degradation and wind erosion (Table 6.1). Of particular importance is to minimize soil or vegetation disturbance in areas where soil types are especially susceptible to wind erosion. Natural source areas are predominantly (85%) non-hydrologic sources, often dry lake beds in arid regions (Section 2.4) and there may still be opportunity for protective measures, but many hydrologic sources in dry areas may already be utilized for human activity. In deserts, many active dunes are mobile, some migrating more than 15 m/yr, causing significant hazards to human activities (Al-Harthi, 2002).

Preventive measures in rangelands include avoiding disruption of microbial soil crusts, overgrazing, burning, or over-utilization, which are major drivers of degradation in semi-arid and arid regions (Ravi *et al.* 2011). In natural ecosystems, protection measures should aim to retain diverse vegetation, reduce fire risk and minimize disturbance of natural crusts by vehicular traffic. For example, disturbance of deserts can disrupt the natural vegetation patchiness leading to increasing connected pathways between bare soil patches, which provide conduits for wind and water erosion and transport, and can lead to desertification (Okin *et al.* 2009).

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, application of chemical surfactants, spreading of gravels, irrigation to dampen the soil surface, mechanical compaction, and paving roads (Gill and Cahill 1992). Synthetic materials such as polyvinylacetate (PVA) emulsions and polyacrylamides (PAM) sprayed on the soil surface have been used to control saline dust blowing from tailing ponds associated with the mining industry (Armbrust and Lyles 1975). There have however been remarkable instances of reclamation of degraded desert land and stabilization of sand dunes through re-vegetation, where water resources allow, despite the high labour requirements involved (Box 6.1).

Table 6.1: Measures to control wind erosion in rangelands and natural ecosystems. Compiled from various sources.

Objective	Control measures
Manage vegetation in rangelands	Reduce burning of grasses and plant litter Maintain perennial grasses Avoid overgrazing through reduced stocking rates or rotational grazing Avoid over-exploitation of trees and shrubs Avoid/reduce disturbance of natural crusts (algal, lichens)
Protect vegetation in natural steppe and desert areas	Retain diverse vegetation cover Reduce fire risk Avoid/reduce disturbance of natural crusts
Fix sand dunes	Planting of dead fences, grasses and shrubs

Box 6.1: Reclaiming land in the Kubuqi Desert, Inner Mongolia, China

Ecological restoration efforts were initiated in the Kubuqi Desert in the late 1980s by the Elion Foundation, initially to protect roads and infrastructure. A successful biological package for sand control was implemented, consisting of fences of straw and bundled shrub stems laid out on a grid pattern. Grasses and trees of *Salix linearistipularis* K.S. Hao (Willow), *Caragana microphylla* Lam. (Pea Shrub) and *Salix psammophila* Z. Wang and Chang Y. Yang (Desert Willow) were then established. Planting was extended to a 4 km wide green shelterbelt along a 65 km road, consisting of *Glycyrrhiza glabra* L. (liquorice), Salix and other trees.

Initial stabilization of sand dunes using checkerboards

Critical to the successful establishment of trees was the innovation of new planting methods such as water jetting, which involves jetting water into the deep sand layer, which creates a hole to aid planting of the shrub cuttings and irrigates at the same time, resulting in very rapid planting. This increased tree survival rate from 20% to over 85% and reduced planting cost.

Water jetting to create a watered hole for planting shrub and tree seedlings

These initial conservation activities were later extended to support a modern pharmaceutical enterprise based on medicinal herbs, especially liquorice. A range of technical innovations were developed for establishing various herbs, shrubs and trees in various planting arrangements, such as mixed species forests and shelter belts.

Favourable hydrological conditions coupled with strong public-private-community partnership were critical for the success of the project. Government enabling policies facilitated private and community involvement and strong partnerships. Elion in particular played a major role in balancing ecological improvement with business operations and infrastructural co-investments. Innovation and adaptive learning were also key success factors.

Source: (UNEP 2015b)

Box 6.1: Reclaiming land in the Kubuqi Desert, Inner Mongolia, China (continued)

Well-established protection belt along the highway 25 years later. The original sand dunes can be seen in the background.

Table 6.2: Measures to minimise wind erosion in crop lands. Compiled from various sources. See glossary for definition of terms.

Objective	Control measures
Reduce periods with little or no soil cover[1]	Adjustment of 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 Multistrata systems Good crop management
Increase soil resistance to wind erosion	Increased input of organic residues through increased crop productivity, organic mulches, manures Reduce soil disturbance through reduced 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

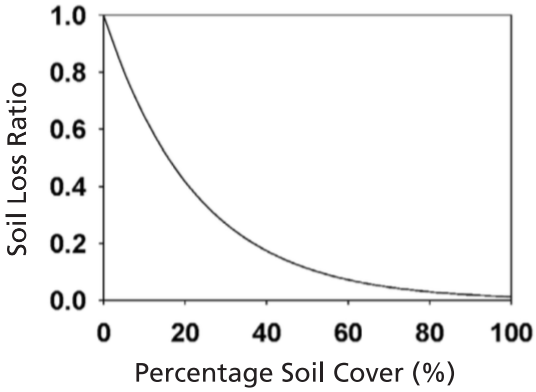
[1] Soil cover is the degree to which soil is protected by vegetation, organic litter layers or mulch

6.2 Control measures in crop land

Strategies for controlling SDS have largely focused on technical measures implemented in cultivated areas, aimed at reducing soil exposure to wind, reducing wind speed or reducing soil movement (Table 6.2). All wind erosion control measures (Mann 1985; Yang *et al.* 2001) are relevant to the control of SDS.

The most fundamental measure is reducing soil exposure to wind by protecting the soil with live or dead vegetation, and 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 help to achieve this objective. Reduced or no tillage and related optimal agronomic practices that minimize soil disturbance and maximize residue cover on the soil surface are often included under "conservation agriculture". Good crop agronomic management practices that increase crop vigour also reduce the time that soil is bare during the cropping season. Good management includes factors such as use of quality planting material, optimal plant density, appropriate soil and crop nutrient management, and adequate pest and disease control.

Figure 6.1: Typical relationship between wind erosion, expressed as the amount of soil loss from a protected soil surface as a ratio of the amount of soil loss from bare soil, and the degree of soil cover. Source: Ravi *et al.* (2011).

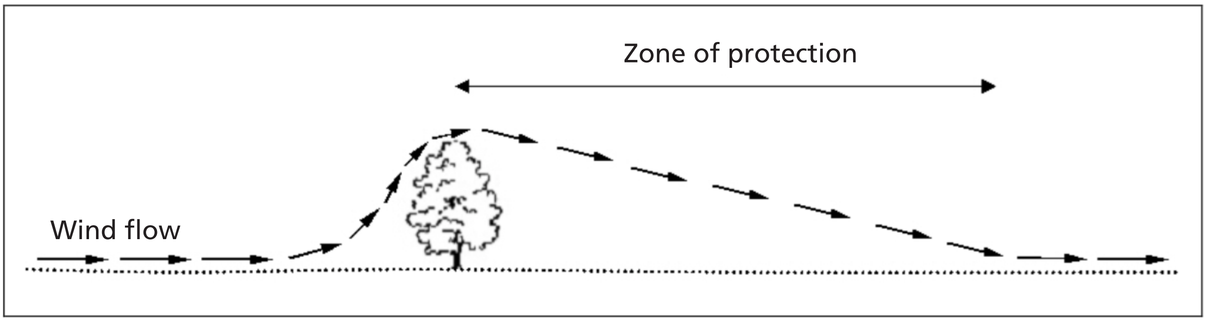


The relationship between wind erosion and live or dead vegetation cover of soil is generally exponential, with larger decreases in erosion per increase in percentage ground cover at low cover (Figure 6.1). Substantial protection can be achieved with only 40-50% soil cover, however, the relationship varies with factors such as vegetation type and soil susceptibility to wind erosion. Near ground cover is most effective in protecting soil against detachment and movement at a given wind velocity.

Crop management practices that increase above-ground or below-ground inputs of organic residues

Reduced and mulch tillage systems providing soil protection from wind erosion in the USA. Source: Tarataka (2016).

Figure 6.2: Protection effect of wind barriers. Source: Tatarko (2016).



to the soil, either through improved productivity or by returning a larger fraction of residues, will increase soil stability and resistance to detachment and erosion, by increasing the threshold velocity required for soil movement or increasing surface roughness (Section 2.3). Reduced tillage slows down the rate of organic matter decomposition. In addition, roots of live vegetation act as a soil binding mechanism.

In resource-poor dryland farming systems there is often competition for use of residues for feed, fuel, compost, or the market, and use of residues for mulch may receive low priority. Use of residues for mulch may be most realistic in farming systems of medium intensification (Tittonel *et al.* 2015). At lower levels of intensification, they are more likely to be used for opportunistic feed or grazing, whereas in more intensive systems cultivated pastures and fodder crops are more likely to be grown. Animal manures can also provide effective protection, even at low levels of cover (de Rouw and Rajot 2004).

Apart from protecting soil and building soil resistance, 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 6.2). Wind breaks can reduce wind speeds by 50 – 80% of the wind speed 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 the height of the windbreak. Windbreak porosity also affects the pattern of wind velocity within the shelter zone. A 20% porosity has been found to maximize the protection distance (Burke 1998). However, the fully protected zone of any barrier diminishes as wind velocity increases and as the wind direction deviates from perpendicular to the barrier (Tatarko 2016).

Agroforestry provides a number of options for providing windbreaks in agricultural land while providing produce and other ecosystem services (Young 1989). These include linear arrangements of trees and shrubs around fields and homesteads, along roadsides, on soil conservation contours within fields, and in riparian areas (Box 8.7). In dryland areas, scattered trees can provide important protection in crop lands (Box 6.2). Wind erosion may not always receive priority from farmers in resource-poor areas (Sterk 2003) and therefore solutions, such as agroforestry, that provide some form of economic incentive are preferable. There is a range of other traditional soil and water conservation measures used in drylands which can help increase vegetation cover and stabilize soils. These include water harvesting techniques, soil conservation bunds, and organic manures (Biazin *et al.* 2012; Schwilch *et al.* 2014).

Shelterbelts and windbreaks protecting crop land in large fields. Source: Tatarko (2016).

Box 6.2: Parkland systems in the West Africa Sahel help to reduce wind speed and soil erosion.

Scattered trees in crop lands in semi-arid areas of the West Africa Sahel, with a typical density of about 15 trees per hectare, help to reduce wind speed and soil erosion. The trees, such as Faidherbia albida and Vitellaria paradoxa (shea), have economic value, and provide fuelwood, fodder, and shade for livestock. During the rainy season, crops such as sorghum and millet are grown among the trees and in the dry season livestock graze on the crop residues. High priority should be given to maintaining these woodlands.

Scattered trees offering protection to crop land and livestock in a Parkland system in Mali. Photo credit: Gemma Shepherd. Source: UNEP (2012).

Farmer managed regeneration of trees in crop land in Senegal. Source World Vision, Australia.

Farmer Managed Regeneration of Trees (FMNR), whereby farmers nurse natural re-growth of trees, was first recognized in Niger in 1983 (Francis *et al.* 2015). It involves centuries-old methods of woodland management techniques, namely coppicing and pollarding, to produce continuous tree growth for fuel, building materials, food and fodder without the need for frequent and costly replanting. FMNR has since spread across five million hectares, or 50 percent of Niger's farmlands and has been introduced in 18 countries across Sub-Saharan Africa, Southeast Asia, Timor-Leste, and most recently India and Haiti.

Mechanical measures can be used to prevent transport of soil particles once they are detached. Tillage practices can be used to bury erodible material and increase the roughness by increasing the percentage of non-erodible aggregates on the surface and creating bed patterns perpendicular to the predominant winds (Nordstrom and Hotta 2004). Mechanical methods can prevent soil transport, but they generally do little to prevent detachment of soil particles (Morgan 1995). The high energy requirements of this approach restrict its appropriateness to intensive farming systems, but tillage may be considered as an emergency measure and the costs may be reduced by using strip tillage as opposed to tilling the whole field area.

Most control practices are completely consistent with concepts of sustainable land management. A database of sustainable land management is available and includes some information on costs (WOCAT 2016), but there is need for further systematic efforts to compile data on production costs and benefits of various practices in different conditions.

6.3 Control measures in industrial settings

Industrial sources of dust, such as mining operations, have specific options for preventing dust from generating 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 stabilise tailing dumpsusing 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 (e.g., Baklanov and Rigina 1988; Amosov *et al.* 2014) have examined effects of different factors and conditions on dust production from tailing dumps, such as wind velocity, humidity and other meteorological parameters, material

Clod forming tillage produces aggregates or clods that are large enough to resist the wind force and trap smaller moving particles, and resist breakdown by abrasion throughout the wind erosion season. Source: Tarataka (2016).

moisture content, size and shape of particles, efficiency of dust catching, height and geometry of tailing dumps, as well as specific measures to reduce dusting, e.g., protection barriers. Numerical modelling studies have indicated the effectiveness of two-metre high protective barriers on the leeward side of tailing dumps on reducing levels atmospheric pollution downwind (Melnikov *et al.* 2013).

6.4 Protection of urban areas and infrastructure

A major challenge is to protect urban areas and infrastructure from unwanted dust and sand deposition from SDS. Reducing wind speed through tree planting, such as shelter belts, around urban areas and infrastructure helps to trap dust and deposit sand outside these areas (e.g., Bird *et al.* 1992). However, impacts on lighter dust particles carried above tree height may be limited.

Wind erosion can result in blowing sand and mobile sand dunes at wind speeds that are too low to generate SDS, which pose an aeolian hazard (Wiggs 2011b) and so measures for protection against blowing sand and dune movement are included below. They tend to be associated with active dunefields and sand transport corridors in drylands where topographic depressions accumulate sand-sand sized material (Figure 2.3). Urban areas and infrastructure, as well as farm land, established on the edges of such areas become susceptible to blowing sand and mobile sand dunes (Wiggs 2011b). Active dunes can migrate more than 15 m/yr, causing significant hazards to human activities (Al-Harthi, 2002).

There are various measures for controlling windblown sand and moving sand dunes, summarized in Table 6.3 and some are illustrated in Box 6.1. Examples of various types of fences used to protect Qinghai-Tibet Railway in China are given by Zhang *et al.* (2011). Various measures deployed to protect infrastructure in Kuwait are summarized by Al-Awdhi and Misak (2000).

Stabilization of sand dunes usually entails 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 by any other material such as plastic sheets, nets, geotextiles, etc. Fences of materials such as straw and tree branches are also frequently used, either as checkerboard or linear arrangements (see Box 6.1 for example). More capital intensive methods using sprays of petroleum emulsion products have been

Table 6.3: Measures for controlling windblown sand and moving sand dunes. Source: Watson (1985).

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 the 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

tested in Libya, Egypt and Kuwait for stabilizing sand dunes prior to establishing vegetation (Granger 1990; Ramadan *et al.* 2010) and are used to stabilize surfaces in some industrial settings.

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. There is need of careful planning of nursery operations to produce the large quantities of material required. 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 drawn down and deplete water tables and die off. Temporary irrigation is often required to ensure plant survival during the establishment phase. Efficient methods for irrigation at planting have been established, such as water jetting (Box 6.1). Options for planting include planting of seedlings, direct sowing and aerial seeding. Sustainable management and harvesting of vegetation is essential for prevention of dune de-stabilization (FAO 2010). Only 15% vegetation cover may be sufficient to stabilize sand surfaces (Lancaster 2011)

Encroaching sands have displaced entire communities, such as the people of the village of Jadallah in Nile state of the Sudan. Source: UNEP.

Trees used to stabilize sand dune encroaching on an irrigation scheme on the Nile flood plain. Source: UNEP.

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Surface stabilization for dust control at an industrial site using soil binding agents applied by a hydroseeder. Source: Bender GmbH & Co.KG.

Aerodynamic methods to harness wind to remove sand from urban or other areas have also been used (FAO 2010). The method aims 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. Removal of obstacles in strips along roads has been used (transverse streamlining) to reduce sand accumulation, for example along the Road of Hope in Mauritania, but this needs constant maintenance (FAO 2010).

6.5 Integrated control strategies

There is need for an integrated multi-scale approach for effective SDS control. Control measures at the field scale to protect soil and reduce wind speed locally, need to be combined with landscape measures over large areas to reduce wind speed, reduce sand and dust mobilization and increase deposition of sand and dust out of the atmosphere. Measures must simultaneously tackle different components of the landscape, including cropland, rangeland and deserts, as well as other sources, such as building sites, mines, etc. Integrated, landscape level measures are especially critical given the transboundary impacts of SDS.

Control of anthropogenic sources of SDS is synonymous with sustainable land management (Kapu *et al.* 2014; World Bank 2008; Young 2014; and integrated landscape management (Minang *et al.* 2014; Sayer *et al.* 2013; Scherr *et al.* 2012) and requires a long-term vision. Particularly relevant is the adoption of sustainable dryland cropping and rangeland management practices, and appropriate protection and management of deserts and other natural ecosystems (Sections 6.2 and 6.1). Since sustainable land and landscape management is also a solution to dryland development, food security, and biodiversity management, as well as an important potential contributor to climate change mitigation and adaptation, there are multiple synergies.

Integrated, including transboundary, management of water resources will be an important component of landscape management. Over-utilization of water, leading to drop in the height of water tables, will have knock-on effects on vegetation cover and susceptibility to wind erosion and desertification. Reduced water storage will also make land more susceptible during drought periods. Water requirements of different land uses and management of water abstraction and water transfers need to be considered (for example, see Box 8.1).

Since 75% of mineral dust emissions are from natural sources, there is a risk of accelerating dust emissions beyond natural levels if these are converted to anthropogenic sources. Therefore protection and sustainable management of natural source areas is an important preventive strategy. Reduction of water flows into ephemeral water bodies will increase the risk of dust emissions if this leads to increased length of dry periods or desiccation of water bodies. Increase in this risk is being driven by demographic, economic, and political pressures, which are all pushing to (i) increase the land area that is affected by human use, and (ii) decrease the amount of water that is used to sustain ecosystem services. Societal benefits (local, regional, global) from sustaining ecosystem water flows will ultimately outweigh the pressures for immediate local gains.

Beyond the above elements of integrated landscape management, there is need for measures to protect human health and infrastructure against mobilized sand and dust. Measures to protect urban areas and infrastructure were described in Section 6.4. Direct measures to protect human health, such as air conditioning or filtering in buildings, and wearing of dust masks during dust storms are additional protective measures. From a preparedness perspective, SDS early warning systems (Section 5) and campaigns to create public awareness of emergency measures are an essential component of integrated strategies.

Climate change, especially increasing climate variability and frequency of extreme events, is an important risk factor for increased SDS from both natural and anthropogenic sources. Hence all climate change mitigation measures (IPCC 2014b; UNEP 2015c) are relevant to decreasing future impacts of SDS.

7. Policy Actions for Mitigating SDS

This section starts by summarising existing policies and actions, first at national and regional levels, and then at a global level. A policy framework for mitigating SDS is then proposed. First key features of SDS, summarised from previous sections of this report, provide the context for framing SDS policy actions. Then a policy framework for mitigating SDS is proposed based on a categorisation of strategic actions. Using this framework, policy options for improving SDS actions are suggested. Finally, a global policy response is proposed.

7.1 Existing regional and national policy actions

This section provides examples of on-going regional actions, and associated national actions, directly focused on SDS mitigation. Other regional and national actions that are also relevant to SDS mitigation are given in Section (7.1.2). In the history of SDS actions, there are positive lessons to be learned from successes in the US and the Regional Action Plan for Northeast Asia, but in contrast there has been a missed opportunity to improve the lives of millions of people in West Asia due to lack of resources to operationalise a well-formulated SDS Regional Action Plan.

7.1.1 SDS regional action plans

Northeast Asia SDS Master Plan

A Regional Master Plan for the Prevention and Control of Dust and Sand Storms in Northeast Asia was jointly initiated and conducted by the Asian Development Bank (ADB), the UNCCD, the United Nations Economic and Social Commission for Asia and Pacific (UNESCAP), and UNEP. Four governments were involved: the People's Republic of China, Japan, the Republic of Korea, and Mongolia (UNCCD 2005). The components of the regional master plan are: (i) a phased program to establish a regional monitoring and early warning network for SDS in Northeast Asia, and (ii) an investment strategy to strengthen mitigation measures to address root causes of SDS in source areas.

The first component is realised within the WMO SDS-WAS Asia Node (see Section 5.1.2). The SDS-WAS Asia Regional Centre is hosted by the China Meteorological Administration (CMA) and involves partners from Japan, South Korea, Mongolia and Kazakhstan. It realises a regional network for monitoring, early warning, and forecasting of SDS (Asia Regional Centre 2016).

The second component was implemented under the guidance and supervision of a technical committee chaired by UNESCAP and focused on: (i) the selection of sites for nine demonstration projects (four in PRC and four in Mongolia and a sub-regional demonstration site that straddles the border of both countries), (ii) the identification of best practices for the demonstration projects for SDS prevention and control, and (iii) the development of an investment strategy that provides recommendations on sustainable financing mechanisms for the promotion and dissemination of best practices in addressing the causes of SDS. Further activities of the Northeast Asia plan are exemplified in Section 7.1.2.

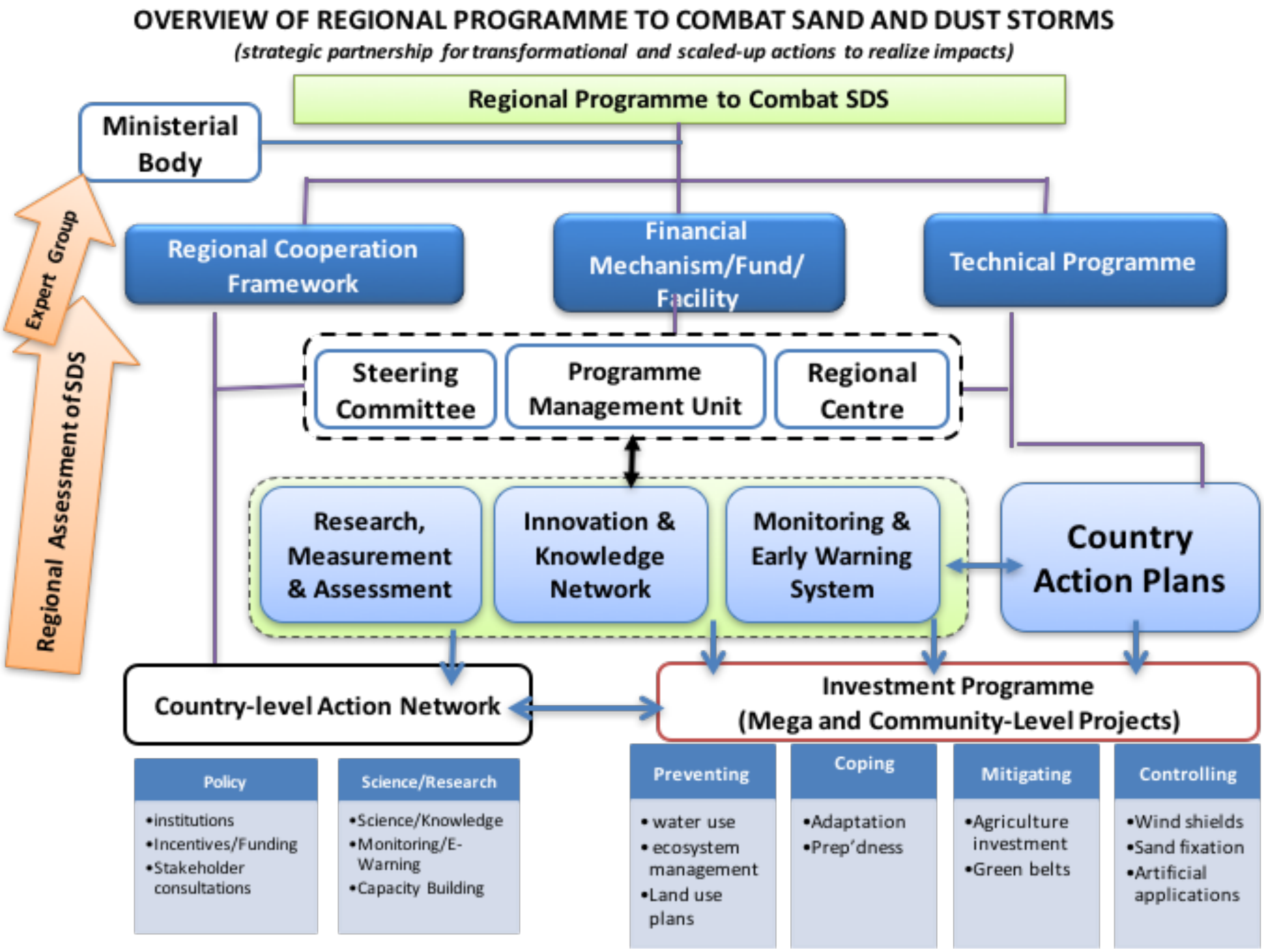
West Asia SDS Regional Master Plan

The West Asia Regional Master Plan to Combat Sand and Dust Storms was drawn up as a result of a number of consultations and meetings of affected countries in the region, coordinated by UNEP and WMO Regional Offices for West Asia, with the help of a task force from UNEP, WMO and the Islamic Republic of Iran (Cuevas, 2013ab; UNEP 2014). The Plan includes Bahrain, Iran, Iraq, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, Turkey, and the United Arab Emirates. The ultimate goal of the programme is to protect people, the environment, and the development agenda of the West Asia Region from the transboundary threats and impacts of sand and dust storms through well-informed and coordinated practical actions. Key objectives include to improve strengthened cooperation among countries on solutions, research and early warning networks. Principal lines of action are to establish the Regional Cooperation Framework, develop and implement the Technical Programme, and establish the Regional Financial Mechanism (Figure 7.1). The Plan was elaborated in some detail and compiled information on SDS in the different countries of the regions, but was not implemented due to lack of funding. Even so, some progress has been made on SDS assessments (Box 8.1 – Box 8.5).

7.1.2 Regional and related national policy actions

This section provides an overview of other regional and related national policy actions on improved land management that are relevant to SDS mitigation.

Figure 7.1: Overview of West Asia regional programme to combat sand and dust storms. Source: UNEP (2014).



UNCCD Regional and National Action Plans

By the request of the Convention, its five regional implementation annexes with sub-regions have developed their own Regional Action Programme (RAP). The West Africa sub-region under the regional Annex for Africa adopted its Sub-Regional Action Programme (SRAP) in 2013 and recognized soil erosion and sand encroachment as a form of land degradation as exemplified in the Lake Chad and laid out four strategic objectives to address regional issues on land degradation (UNCCD 2013).

In the regional implementation annex for Asia-Pacific region, the implementation is advanced by the promotion of regional cooperation and capacity-building at national and sub-regional levels through the six Thematic Programme Networks (TPNs) including the rangeland management and fixation of shifting sand dunes. The TPN on the rangeland management and fixation of sand dune hosted by Iran was aligned with the West Asian SRAP adopted in 2000.

The Central Asia sub-region identified the transport of dust from the desiccated lake bed of the Aral Sea and the increasing levels of aerosols in the air as a sub-regional issue. The Central Asia sub-region set pasture management as a priority, which will be coordinated with regional actions on sand stabilization. In regard to the sub-regional activities, Uzbekistan included fixation and afforestation of moving and dried bottom of the Aral Sea as a priority pilot project. The National Action Plans (NAPs) of Turkmenistan, prepared in 1997, identify stabilization and afforestation of moving sand as one of the priorities (UNCCD 2003).

The Northeast Asia Network for Desertification, Land Degradation and Drought (DLDD-NEAN), a sub-regional reporting entity to the UNCCD, adopted its sub regional action programme (SRAP) entitled "The Northeast Asia Sub-Regional Action Programme for Combating Desertification and Dust and Sandstorm" in 2008 (Box 7.1). The Northeast Asia SRAP recognized SDS as a sub-regional issue and proposed cooperative activities including among others (i) information sharing, (ii) joint research and field studies, (iii) capacity building, (iv) technology transfer, and (v) implementation of joint projects. Under the SRAP, with the support of the UNCCD, the DLDD-NEAN developed a joint demonstration project for prevention and control of dust and sandstorms. This pilot project is conceptualized based on the information of the Northeast Asia SDS Master Plan (see Section 7.1.1) and is being refined for further implementation.

Among 168 affected countries under the UNCCD, 107 countries (or 64% of affected country Parties) were due to have completed the NAP revision process by the end of 2015. However, the exercise should be completed in the course of 2016/2017 through a voluntary quantitative target on Land Degradation Neutrality (LDN), as defined by the Sustainable Development Goals (SDGs) and the COP (UNCCD 2016a).

Green Wall initiatives

China has one of the earliest and most ambitious programmes to combat desertification, initiated under its commitments to the UNCCD (Box 8.8). There is some evidence of positive impacts of desert reclamation in China on dust reduction (UNEP 2015b). In a similar initiative to the Great Green Wall of China, the African Union, with the support of the World Bank is establishing a Great Green Wall of

Box 7.1: Sub-regional cooperative frameworks and mechanisms in addressing SDS in the Northeast Asia

- Northeast Asia Network for Desertification, Land Degradation and Drought (DLDD-NEAN) was originally established as the “Northeast Asia Forest Network” in 2007 and expanded into the DLDD-NEAN in 2011 during UNCCD COP 10. Its active members include China, Mongolia and the Republic of Korea. The DLDD-NEAN is an official reporting entity to the UNCCD and operated by the Steering Committee which meets annually in conjunction with a forum to discuss thematic sub-regional issues.
- North-East Asian Sub-regional Programme on Environmental Cooperation (NEASPEC), launched in 1993, which is an intergovernmental cooperation mechanism on environmental issues including “desertification and dust and sandstorms”. Its operation is supported by the permanent secretariat at UNESCAP East and North-East Asia Office. It has six country memberships (China, DPRK, Japan, Mongolia, ROK and the Russia). NEASPEC participated in developing a Regional Master Plan in 2005, conducted jointly by ADB, UNESCAP, UNEP and UNCCD.
- Tripartite Environment Ministers Meeting among the Republic of Korea, Peoples Republic of China and Japan (TEMM) is held annually since 1999 to promote and strengthen cooperation on environmental issues. Among the agenda of the TEMM, issues on dust and sandstorm (2006) and transboundary air-pollution are included (2012). In order to manage a variety of environmental cooperation activities, TEMM adopted the first “Tripartite Joint Action Plan on Environmental Cooperation (TJAP) 2010-2014” in 2010, containing ten priority areas including SDS. The second TJAP (2015-2019) adopted in 2014 included “air quality improvement” as one of its nine priority areas. Two working groups (WGI and WGII) were established to facilitate the implementation of air quality improvement (TEMM 2015). TEMM endorsed the Mid-term Action Plan of WGI and WGII for Joint Research on Dust and Sandstorms (2015-2019) at its meeting in 2015.
- The Tripartite Presidents Meetings (TPM) among the national environmental research institutions of China, ROK and Japan have been held since 2004 for the purpose of enhancing environmental research cooperation. The participating agencies are; the National Institute of Environmental Studies (NIES, Japan), the National Institute of Environmental Research (NIER, ROK) and the Chinese Research Academy of Environmental Sciences (CRAES, China). Among the eight cooperative priority areas, “air pollution including vehicle pollution and trans-boundary air pollution” and “dust and sandstorm” are included.
- The UNCCD, with support from the Korean Government, conceptualized a project based on the information in the master plan and commissioned a feasibility study (2013) to support the subregional activity of DLDD-NEAN. Based on the feasibility study, the DLDD-NEAN decided to implement this project and financial support was made available to the UNCCD through the Changwon Initiative (through a sub programme, the Greening Drylands Partnership, see section 7.2.1). This project is now further refining its implementation plan.

trees, grasses and shrubs along the southern edge of the Sahara Desert (Box 8.9). The Great Green Wall project aims to re-vegetate 15 million hectares along a 15 km-wide, 7,775 km-long belt, from Dakar to Djibouti. It aims to be both a soil conservation effort and in doing so help create more sustainable land management and grow more food. For such initiatives to be successful in the long-term, they need to carefully consider available water resources, use well-adapted plant species and provide economic products (UNEP 2015b).

Other national actions

The Republic of Korea has been much affected by dust blown from neighbouring countries and in response has developed the first Master Plan for Asian Dust Damage Prevention (2008-2012). This master plan is prepared in response to the Article 13 of the "Clean Air Conservation Act" amended in 2008. The First Plan was prepared with the participation of 14 relevant governmental organizations. The main focus of the first Plan was to: (i) establish a platform for monitoring of dust storms, (ii) develop actions to protect against damage, (iii) establish the Northeast Asian sub-regional cooperation network, and (iv) strengthen disaster management. The second phase of the Plan (2013-2017) was prepared around a precautionary approach as disaster risk management and gave special attention to vulnerable population groups. The characteristics of the Second Plan include strengthening the SDS monitoring network to enhance SDS forecast capacity, a risk management plan for vulnerable population groups and different sectors including health, food, and air transportation, and regional cooperation for SDS mitigation (Park 2013).

Iran has initiated a number of agreements on SDS including regional and bilateral action plans with neighbouring countries (Box 8.10). These cover joint activities on monitoring, training and land restoration.

7.1.3 Regional air pollution policies

There are a number of regional air pollution agreements and policies that have potential to specifically address SDS. Some examples are summarised below.

- The Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effects for South Asia is an intergovernmental agreement to tackle regional air pollution problems, established in 1998 by the South Asian countries at a meeting of the South Asia Cooperative Environment Programme (SACEP) Governing Council. The Malé Declaration is partly being resourced through the Regional Air Pollution in Developing Countries (RAPIDC) Programme.
- Regional Air Pollution in Developing Countries (RAPIDC) aims to facilitate the development of agreements/ protocols to implement measures which prevent and control air pollution. The emphasis is on capacity building to promote the generation of regionally specific information on air pollution issues.
- The Air Pollution Information Network for Africa (APINA) was formed in 1997 and acts as a link between different networks and programmes on air pollution in Africa. Southern Africa is APINA's main focus region but activities also reach out across the whole of Sub-Saharan Africa.
- The Governments of the ten ASEAN (Association of Southeast Asian Nations) member countries signed the ASEAN Agreement on Transboundary Haze Pollution in 2002. The Agreement is the first regional agreement that binds a group of countries to tackle transboundary haze pollution resulting from land and forest fire. The Agreement establishes an ASEAN Coordinating Centre for Transboundary Haze Pollution Control to facilitate cooperation and coordination in managing the impact of land and forest fires in particular haze pollution.
- China – South Korea – Japan joint SDS cooperation within the Asia Node of SDS-WAS.
- China – South Korea – Mongolia joint SDS monitoring (see Box 7.1). Mongolia and Kazakhstan are associated partners of the Asia Node of SDS-WAS.
- The Northeast Asia Sub-regional Program of Environmental Cooperation (NEASPEC; see Box 7.1).
- The Convention on Long-Range Transboundary Air Pollution is intended to protect human and environment against air pollution and to gradually reduce and prevent air pollution, including long-range transboundary air pollution exchange. It was signed in 1979 and entered into force in 1983. It has given rise to eight specific protocols, covering acidification, eutrophication and ground level ozone, persistent organic pollutants, heavy metals, sulphur, volatile organic compounds and nitrogen oxides.

7.2 Existing global policy actions

This section provides an overview of major on-going global policy actions relevant to SDS mitigation. It covers the Rio conventions, international environmental law for SDS, and institutional development on monitoring, prediction and warning systems for SDS.

7.2.1 The Rio conventions and associated support

Actions required to tackle the drivers of SDS are consistent with actions recommended to tackle land degradation, terrestrial biodiversity and climate change mitigation under the three respective Rio conventions – the United Nations Convention to Combat Desertification (UNCCD), the United Nations Convention on Biological Diversity (UNCBD) and the United Nations Framework Convention on Climate Change (UNFCCC).

The UNCCD, adopted in 1994, is a unique international instrument dealing with land degradation in arid, semi-arid, and dry sub-humid area of the world where most SDS originate. The UNCCD directly encompasses combatting land degradation as part of the definition of desertification within the objective of the convention and with well-defined references to and implications for land use and land degradation (Dooley *et al.* 2015; UNCCD 1994). Since it first came into force in 1996, with an aim to combat desertification and mitigate the effect of drought, the UNCCD has broadly contributed to address the issues of mitigating SDS considering the linkage to land degradation as a cause of SDS (Squires 2001).

In 2007, the UNCCD adopted the 10-year strategic plan and framework to enhance the implementation of the Convention for 2008-2018 (the Strategy). The Strategy is tasked to provide a global framework to combat desertification and land degradation with four strategic objectives including “to improve the condition of affected ecosystems”, which encompasses SDS. The most recent international commitment to address land degradation is the adoption of the Land Degradation Neutrality (LDN) target of the Sustainable Development Goals (SDGs). The SDG Goal 15 is to “Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss”. In particular, SDG target 15.3 addresses “By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land-degradation-neutral world”. Implementation of the LDN target will improve the quality of degraded land and reduce future land degradation through the adoption of sustainable land management and land restoration practices. This effort will positively contribute reducing desertification and pressure on deserts and desert margins due to human disturbances, which will in turn reduce new sources of SDS (Gong *et al.* 2004; Squires 2001). The Changwon Initiative, launched in 2011 during UNCCD COP10, is an example of voluntary commitment to Land Degradation Neutrality. The Greening Drylands Partnership, as a sub programme of the Changwon Initiative, provides opportunities to practically test the theories and policies to restore degraded land (UNCCD n.d). Other internationally agreed goals and themes related to land are summarised in UNEP (2015d).

The UNCBD has provisions of relevance for land and land degradation. For example, Article 6 of the CBD contains rules on “general measures for conservation and sustainable use”. Many of the Aichi Biodiversity Targets may contribute to Land Degradation Neutrality (Dooley *et al.* 2015), and three targets (target 7, 14 and 15) are particularly relevant to Land Degradation Neutrality. Article 8 (f) of the text of the CBD, “Rehabilitate and restore degraded ecosystems and promote the recovery of threatened species, inter alia, through the development and implementation of plans or other management strategies” can provide the basis for ecosystem restoration that will be an essential part of the action needed to achieve Land Degradation Neutrality. CBD decisions XII/19 (Ecosystem conservation and restoration) and XI/16 (Ecosystem restoration) will provide further guidance for ecosystem restoration. The Hyderabad Call for Concerted Action on Ecosystem Restoration, announced at CBD COP 11, will help to achieve many of the Aichi targets including 15 on restoration of degraded ecosystems and striving towards LDN. There is on-going discussion on a short term action plan on ecosystem restoration. Increasing or maintaining dryland biodiversity in agricultural landscapes, rangelands, deserts, and other natural ecosystems, is compatible with vegetation and soil management actions required for sustainable land management and reduction of wind erosion (see Section 6).

The UNFCCC aims at “prevent[ing] dangerous anthropogenic interference with the climate system” (Article 2 UNFCCC). All climate change mitigation measures across all sectors are relevant to reducing SDS risks due to the importance of drying climate regimes and increasingly extreme climatic events as drivers. The UNFCCC also has a number of provisions that are of relevance for the prevention of land degradation, such as Article 3(3) UNFCCC, requiring parties to "anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects" on all relevant sink and reservoirs of greenhouse gases, which include land, soil and forest. Agriculture, Forestry and Other Land Use (AFOLU) emissions account for about a quarter (~10–12 Gt CO_2eq yr-^{1}) of net anthropogenic GHG emissions mainly from deforestation, agricultural emissions from soil and nutrient management and livestock (UNFCCC 2014). AFOLU is also considered to be central to food security and sustainable development. The most cost-effective interventions have been identified as afforestation, sustainable forest management, and reducing deforestation, cropland management, grazing land management, and restoration of organic soils (UNFCCC 2014b). The Paris Agreement, adopted in 2015, and related provisions on the intended nationally determined contributions (INDCs) further facilitate target setting to reduce anthropogenic greenhouse gas emissions, including from forest and land degradation. Implementation of these interventions in dryland areas will be key to reducing future anthropogenic emissions from SDS.

There has recently been a surge of commitments in support of land restoration initiatives, especially those announced at the UNFCCC COP21 in Paris in December 2015. The Global Mechanism of the UNCCD have proposed a new LDN Fund - a collaborative undertaking, anchored on achieving the Land Degradation Neutrality target of the Sustainable Development Goals (UNCCD 2016a). This supports the LDN challenge: a global commitment to restore 12 million hectares of land per year. Initiative 20x20, launched in 2014, is a country-led effort to begin restoration on 20 million ha of land in Latin America and the Caribbean. Already more than 25 million ha and USD 850 million are pledged across eleven countries. The African Forest Landscape Restoration Initiative (AFR100) is a new country-led effort to restore 100 million ha of land and 10 countries have already committed 32 million ha. The Forest and Landscape Restoration Mechanism (FLR Mechanism), established during the 22nd Session of the Committee on Forestry of FAO in 2014, aims to contribute to scaling-up, monitoring and reporting of FLR efforts for improved resilience, productivity and socio-economic value from restored forest and landscapes.

The French Government launched the "4 per 1000" initiative to increase global soil carbon stocks as a climate change mitigation and food security strategy (French Ministry of Agriculture, Agrifood and Forestry 2016). Launched under the Lima Paris Agenda for Action (LPAA), 140 ministries and organizations have already signed. The World Bank, GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), the World Resources Institute (WRI), the International Union for Conservation of Nature (IUCN) and other donors and development organizations support a number of these initiatives. Examples of national initiatives include the Sustainable Land Management Program of Ethiopia, budgeted at USD 7.5 billion and the German program 'Soil Rehabilitation for Food Security' is a 40 million Euro investment in restoring degraded soils in Kenya, Ethiopia, Benin, Burkina Faso and India. The Consultative Group for International Agricultural Research (CGIAR) is preparing a major research for development initiative for 2017-2022 on restoring degraded lands (WLE 2016).

7.2.2 International environmental law specific to SDS

At its 81st meeting of the 70th session (2015), the United Nations General Assembly (UNGA) adopted a resolution entitled "combating dust and sand storm" (A/RES/70/195). In the resolution, the Assembly recognizes "dust and sand storms in the last few years have inflicted substantial socioeconomic damages" and "the unsustainable land management practices that can cause or exacerbate these phenomena". The resolution encourages continued sharing of best practices, experiences and technical expertise and promotion of regional cooperation on dust and sand storms.

From a disaster risk reduction perspective, the SDG target 11.5 is relevant: "By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations". In particular, Target 11.b requested to "adopt and implement integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels" (UNISDR 2015). The Sendai Framework will guide activities related to disaster risk management including SDS. More generally, SDS is a threat to livelihoods, environment and economy that could undermine the implementation of a broad range of the SDG targets. Studies such as Gianndaki *et al.* (2014) provide insight on dust impacts on mortality at global level and could assist in implementing policies for risk reduction due to dust.

The Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts under the UNFCCC provides a window to address SDS related issues. Established by the UNFCCC COP Decision 2/CP.19 in 2013, the Warsaw International Mechanism aims to address loss and damage associated with the adverse effects of climate change, including extreme events and slow onset events, in a comprehensive, integrated and coherent manner. The Warsaw International Mechanism will promote the implementation of approaches to address loss and damage, inter alia, by enhancing knowledge of comprehensive risk management approaches, which is a core component of SDS policy. The Warsaw International Mechanism can facilitate actions to address gaps in understanding on losses and damage resulting from SDS, for example, on risk assessment and non-monetary losses.

7.2.3 Monitoring, prediction and warning systems for SDS

The WMO provides global coordination of monitoring, prediction and warning systems for SDS (see Section 5 for details). The Global Atmosphere Watch (GAW) programme of the WMO is a partnership involving the Members of WMO, contributing networks and collaborating organizations and bodies. GAW provides reliable scientific data and information on the chemical composition of the atmosphere, its natural and anthropogenic change, and helps to improve the understanding of interactions between the atmosphere, the oceans and the biosphere. GAW observational networks are using harmonized measurement techniques, and GAW has data centres with global responsibility.

Within the World Weather Research Programme (WWRP) and GAW, WMO coordinates the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). SDS-WAS was established in 2007 in response to the intention of 40 WMO member countries to improve capabilities for more reliable sand and dust storm forecasts (see Section 5.1). SDS-WAS focuses on real-time delivery of products and research to improve forecasting products from atmospheric dust models to reduce SDS risks for societal benefit. More than 15 organizations currently provide daily dust forecasts in different geographic regions (Table 5.1), including use of six global models (Table 2.1). The SDS-WAS integrates research and user communities, such as medical, aeronautical, and agricultural users. SDS-WAS is established as a federation of partners organized around regional nodes. To present, the global SDS-WAS Steering Committee and three regional nodes have been established: the Northern Africa-Middle East-Europe Node (hosted by Spain) and the Asian Node (hosted by China) and the Pan-America node (hosted by Barbados), described in detail in Section 5.1.

Other initiatives dealing with air quality currently do not explicitly consider mineral dust but may have scope for doing so, for example, the Climate and Clean Air Coalition (2016) is the only global effort uniting governments, civil society and the private sector that is committed to improving air quality and protecting the climate in the next few decades by reducing short-lived climate pollutants across sectors.

7.3 Policy framework for improving SDS actions

There are already substantive policy initiatives and actions in place that are relevant to SDS mitigation, described in Sections 7.1 and 7.2. This section suggests a policy framework specifically for mitigating SDS. The framework is also relevant for managing the related problems of wind erosion and sand encroachment. First the key features of SDS are summarised from the preceding sections to provide the context for further policy action, before outlining the policy framework. The final sections suggests areas where further investments could fill critical gaps and add value to on-going initiatives for effective SDS mitigation, including suggestions on policy and institutional arrangements for enabling these actions.

7.3.1 Context for further policy action – summary of key SDS features

Key SDS features are summarised below, synthesised from the preceding sections, to provide the context for policy actions for reducing anthropogenic causes of SDS and reducing the negative impacts of SDS:

1. About 75% of global dust emissions derive from natural sources, mostly deserts, and have a number of beneficial effects in sustaining global ecosystems, such as maintaining the nutrient balance of natural forests. Therefore, actions should aim not to eliminate SDS but rather protect ourselves from their negative impacts.
2. The costs of SDS in terms of damage to human health, agriculture, infrastructure, and disruption of operations are substantial. The socio-economic and health consequences, coupled with the above environmental impacts, warrant actions to both prevent SDS and protect human systems against them.

3. There is a risk that human actions could increase SDS emissions in future with uncertain outcomes for the environment. The interactions of dust with global biogeochemical cycles, and with climate system components (both directly and indirectly through these cycles), are complex and profound. Therefore as a precautionary measure, actions should aim to reduce sources of anthropogenic emissions.

4. Anthropogenic emissions result primarily from disturbed soils – those affected by cultivation, deforestation, erosion, overgrazing, or industrial activities. Unsustainable land use is the biggest risk of increased human-induced SDS and damage to ecosystems from wind erosion, especially in dryland regions on sensitive soils. Therefore, all actions required for sustainable land and landscape management are relevant to reducing future SDS risks. This includes not only sustainable management of agricultural areas but also protection of deserts and other natural dryland ecosystems through active participation of local communities and diversification of livelihood options.

5. Climate change, especially increased frequency of extreme weather events, is a major driver of SDS from both natural and anthropogenic sources. Greater future climatic variability and extremes will translate into more frequent and severe SDS. Therefore, all actions designed to mitigate climate change (e.g., according to the 2015 Paris agreement and through INDCs) are relevant to reducing future SDS emissions. This is especially important to note, as above a certain threshold of storm intensity protective measures may have limited effect, and the climate system may cross a tipping point if dust emissions continue to rise.

6. SDS transcend political boundaries, requiring internationally coordinated actions. Wind, the primary agent of SDS, is affected by land characteristics over large distances and deposition can occur at hundreds to thousands of kilometres from the source, often crossing from one region or continent to another. Therefore, an integrated multi-scale approach is required for effective SDS control. Control measures at the field scale to protect soil and reduce wind speed locally, need to be combined with landscape measures over large areas to reduce wind speed, reduce sand and dust mobilization and consequently decrease the density of suspended particles. Measures must simultaneously tackle different components of the landscape, including management of watersheds, forests, croplands, rangelands, and natural ecosystems such as lakes, marshlands and deserts, as well as other source areas, such as building sites, mines, etc.

7. SDS frequency and severity have increased in recent decades in some areas but decreased in other areas. There is evidence to support positive impacts of improved land management on reducing SDS in some areas. Regions that are currently dusty areas and which are likely to become drier include most of the Mediterranean areas of Europe and Africa, northern Sahara, central and west Asia, southwest USA, and southern Australia. Dusty regions that are likely to become wetter include eastern Africa and east and west Asia, whereas large model uncertainties preclude projections for the Sahel-Sudan, the Gangetic basin and the Lake Eyre region. An intensification of dust sources is expected in the tropics due to reduced rainfall, and improvement in sustainable land management practices may be important to mitigate these effects.

In summary, SDS is a problem that transcends political boundaries with significant environmental, socio-economic and health impacts at local to global levels. Human-induced causes of sand and dust storms, including climate change and unsustainable land use in dryland areas, are projected to become more pronounced over the next several decades, but with global consequences. There is an imperative to reign-in human-induced causes of SDS. Preventive measures need to be linked to on-going initiatives in addressing land degradation and climate change at multiple scales. Since most global dust emissions are from natural sources, in the short to medium-term, there is need to reinforce protective strategies to reduce negative impacts of SDS on human health, infrastructure and operations. Measures to protect valuable assets through green barriers and timely early warning systems coupled with preparedness and emergency procedures to minimize impacts on human health are imperative. This will require an integrated approach through regional and sub-regional cooperation at local to global scales.

7.3.2 Framework for policy action

Given the above context, the main types of policy actions identified in this report for mitigating SDS, as well as wind erosion and sand encroachment, are categorised and assembled below to provide an integrated framework for SDS mitigation:

1. Measures to reduce anthropogenic emissions
    a. Sustainable land and landscape management
        i. Protection of croplands by reducing soil exposure to wind, reducing surface wind speed or reducing soil movement through protective cultivation practices and incorporation of wind breaks through agroforestry (see Section 6.2)
        ii. Control measures in rangelands and natural ecosystems through land use planning, sustainable rangeland management and sustainable forest management, protection of vegetation and biological crusts in natural ecosystems, especially deserts, and sand dune fixation through vegetative approaches (see Section 6.1)
        iii. Control measures in industrial settings through dust collection and stabilization of loose surfaces with water or chemical substances (see Section 6.3)
        iv. Integrated landscape management, combining sustainable management of all the above landscape elements, including integrated water management.
    b. Climate change mitigation and adaptation
        i. Climate change mitigation measures at a global level. Available options are described in IPCC (2014b). Sustainable land and landscape management also plays a role in global climate mitigation, through reducing emission of greenhouse gasses and sequestering carbon in vegetation and soil.
        ii. Adaptation to climate change is relevant in terms of coping strategies for SDS impacts and reducing vulnerability, including through capacity building and transfer of technology.
2. Physical protection of valuable assets, such as towns, infrastructure, and irrigation schemes (see Section 6.4)
    a. Reducing wind speed through tree planting around urban areas and infrastructure to deposit sand and trap dust outside these areas
        i. Windbreaks around urban areas, along roads and other infrastructure
        ii. Sand dune fixation with vegetation or chemical substances
    b. Aerodynamic methods to prevent sand and dust accumulation, such as alignment of roads, removal of obstacles to wind and land shaping
3. Monitoring, prediction and warning systems for SDS (see Section 5)
    a. Monitoring of SDS through ground networks of meteorological and air quality monitoring stations, and combined use of satellite data
    b. SDS forecasting and early warning systems, including mapping of trends and future scenarios of anthropogenic dust sources
4. Preparedness and emergency response procedures
    a. Preparedness and emergency procedures for coping with SDS events (e.g., for airport, rail and road closures; hospital emergency services; advisory communications to public services)
    b. Public awareness of SDS risks (via education, media and social networks and telecommunication) and emergency procedures
    c. Mainstreaming SDS into disaster risk reduction and emergency response measures
5. Policies, legal frameworks and action plans to support the above actions (see Section 7).
    a. International environmental law (e.g., Rio Conventions; SDG Target 15.3 on Land Degradation Neutrality) and initiatives (e.g., SDS-WAS)

    b. Regional frameworks, agreements and action plans
    c. National action plans
6. Research to reduce critical uncertainties
    a. Improved knowledge on the interaction of dust with biogeochemical global systems and climate systems
    b. Improved methods for monitoring, prediction and early warning systems
    c. Assessing the impacts and costs of SDS at local to global scales

7.3.3 Policy options for improving SDS actions

Given the mitigation measures identified in this report and the review of existing policy actions, suggestions and options for improving SDS mitigation actions are proposed below.

Measures to reduce anthropogenic emissions

Sustainable land and integrated landscape management practices and climate change mitigation options are generally already well known as methodologies for mitigation of the anthropogenic SDS source areas (Section 6). Greatest attention needs to be paid to integrated landscape management in potential source areas, combining sustainable management of all landscape elements, including integrated water management and reduction of dust from industrial sites. Landscape approaches are becoming increasingly accepted but at a national level integration across various ministries still often poses challenges. Policy will need to focus on providing better incentives and removing barriers for widespread adoption of good practice, a challenge that the Rio Conventions and many supporting institutions and governments are already taking up. There has been less attention to tackling the distal (indirect) drivers of land degradation, and yet preventive measures, especially in dryland areas, could have large impacts on reducing the future burden of land degradation and reducing risk of increased SDS. Continued support for these areas, especially in drylands, will be key to long-term reduction in anthropogenic dust emissions. Suggestions for better global coordination of actions and institutional support rest largely with implementation of the three Rio conventions, which were described in Section 7.2.1.

Physical protection of valuable assets

Practices for physical protection of valuable assets, such as towns, infrastructure, and irrigation schemes, against sand and dust in depositional areas are generally well known (see Section 6.4). Locally adapted, vegetative (green) approaches are to be preferred, especially if they can be linked to economic products and value chains, however constraints posed by climatic regimes and water resource availability need always to be considered.

Greater synthesis and exchange of existing knowledge on green technology and associated economic opportunities across countries and regions could generate value and could be facilitated by a global initiative to synthesize knowledge of best practices. This may build on existing initiatives to synthesis and disseminate knowledge on sustainable land management practices, such as the World Overview of Conservation Approaches and Technologies (Giger *et al.* 2015) and the UNCCD Scientific Knowledge Brokering Portal. The WMO SDS-WAS centres could also provide a platform for knowledge dissemination.

Monitoring, prediction and warning systems for SDS

Given that 75% of global dust emissions are from natural sources and that anthropogenic sources are likely to increase over the next several decades, protection measures are paramount. Monitoring, prediction and early warning will be critical for mobilizing emergency responses, as well as for prioritising long-term sustainable land management measures and providing the data for improved understanding of impacts of SDS on the environment.

Continued efforts towards creating a Global Dust-Health Early Warning System (D-HEWS, see Section 5.4), building on the WMO SDS-WAS initiative, that both utilizes current WMO SDS and other institutional capabilities and influences future directions of WMO SDS, would seem an efficient option. Indeed, global support to individual countries to develop the capacity needed for interpretation and response, would seem more efficient than every country independently developing their own systems. There is good global and regional knowledge on the spatial distribution of the main source areas of SDS (see Section 3) and on the areas they impact and this may be used to prioritise support to countries on early warning. In addition, an assessment of existing early warning capacity may help to prioritise support needs. Investment in the linkages between early warning information and required emergency responses is an area for greater attention. These initiatives would be supported by closer collaboration with UN programmes for SDS policies and adaptation/preventive measures, and global coordination (through the SDS-WAS Steering Committee) of the regional SDS-WAS nodes and relevant SDS activities, involving other UN Agencies. This includes further development of the Pan-America node and establishing the West Asian sub-node (with two clusters).

Knowledge synthesis and capacity development more broadly on SDS, including on (i) potential SDS impacts, (ii) preventive and protective measures, (iii) early warning, preparedness and early response procedures, and (iv) research coordination, could facilitate more effective regional and national action. Options are to build these into a global early warning centre or implement them through a virtual centre or network. The initiative could also play a role in mobilizing resources for these supporting activities.

Emergency response procedures

Preparedness and emergency response procedures in depositional areas need to cover diverse sectors, such as public health surveillance, hospital services, air and ground transportation services, and public awareness and resilience. Since emergency response services are generally applied at a local level further sub-national level reviews and planning are needed.

There is need for a global initiative to develop best practice guidelines and build national capacity in SDS preparedness and emergency responses across different sectors, drawing on the experience from different regions and countries. Options include to attach this service to the global early warning centre (see above) and stronger engagement of UNIDSDR.

Research to reduce critical uncertainties

Large uncertainties remain on the role of dust in global systems and the feedbacks between land, oceans, atmosphere and climate, as well as interaction with climate change. There are many possibilities in terms of research topics and questions and a process of prioritisation would help to better justify limited research resources. A focus on what are the key decision dilemmas facing governments and the global community, and which are the key uncertainties preventing better decision making could be one way to help the prioritisation process. Various areas of research to consider in the prioritisation process could include, for instance: how to better predict SDS for early warning; which are the main dust storm trajectories in all regions over the next 20 years; mapping of vulnerable populations and future trends/scenarios; how to include dust in climate change models; how to better predict anthropogenic dust sources; how to best develop preparedness and emergency response procedures; and which geographical areas and landscape management approaches are highest priority for source mitigation. Better data on the economic impacts of SDS and the costs and benefits of alternative preventive and protection strategies would help to make a clearer case for investments in SDS actions and their synergy with land and climate actions. Finally, representing the true state of the uncertainty in our knowledge in forecasts and modelling studies, and projecting that uncertainty into potential outcomes, would better serve decision making than using deterministic models that provide a superficial level of precision.

Main research needs for further development of the WMO SDS-WAS, formulated in its science and implementation plan for 2015-2020 (WMO 2015), include:

- Model validation and inter-comparisons
- Better understanding and quantifying source regions and effectiveness of possible interventions
- Observation network and near real time data access
- Assimilation of data from different monitoring sources
- Dust interaction with radiation and clouds and impacts to weather and climate using online coupled meteorology-dust models
- Chemical and physical characterization of dust and impacts
- Health effects, such as dust links to meningitis and valley fever

A global initiative to provide research coordination, decision-focused priority setting and support, and research synthesis on SDS would generate efficiencies in terms of resource use and enhanced research impact. This initiative could also be a component of a global SDS virtual centre, based on the WMO SDS-WAS and involving other UN Agencies and interested countries and organisations (see Section 7.3.4).

7.3.4 A global policy response

A consolidated and coordinated global policy directly responding to SDS is proposed to help create awareness of the potential for integrated and synergistic actions across sectors and foster strengthened cooperation among relevant institutions at a global level. This may include the following components:

1. Integrated systems for SDS early warning, monitoring and impact assessment, including globally quantitative and measurable criteria for long term SDS management (WMO)
2. Strengthening of partnerships and actions for mitigating SDS at sub regional and regional levels, including legal commitments by developed and developing countries (WMO, UNEP, UNCCD)
3. A strategy of source mitigation targeted to high risk source areas (UNCCD, UNEP, FAO)
4. Indicators and source monitoring (UNEP, UNCCD, WMO)
5. Disaster risk management strategies (UNIDSDR)
6. Knowledge-sharing on best practices, capacity building and outreach communications
7. Strengthening of linkages to land policy and climate policy, and to legislative and regulatory measures on air pollution
8. Scientific research on SDS impacts on terrestrial environment, climate, biodiversity, oceans, and human health (UNCCD, IUCN, IOC-UNESCO, UNCBD, IPBES, UNFCCC, UNEP, WHO)
9. Regional and international funding mechanisms to cover the cost of SDS related activities

SDS actions could be more specifically integrated into those regional strategies that align with existing global entities such as the UNCCD, UNFCCC, and UNCBD, for instance through UNCCD regional and national action plans. Adoption of the SDG LDN target (15.3) will serve a strong platform to strengthen collective efforts to address SDS in terms of sustainable land management, including management of natural source areas. SDS source mitigation could also be linked to the LDN target setting and included as a voluntary sub-target. Establishing baselines on SDS source areas and emissions and integration of SDS into national-level voluntary LDN targets within their NAPs would support UNCCD policy (Decision 2, COP12). Establishing baselines and monitoring of sustainable land and water management in potential source areas could be a cost-effective proxy approach given its importance as a risk factor for SDS. National action plans and target setting should consider preventive actions in potential source areas in addition to actions to restoring already degraded land.

The coordinated global policy could be initiated by establishing a policy dialogue framework at global level among existing instruments including UNCCD, UNEP, WMO, UNFCCC, UNCBD, and UNISDR, perhaps also as part of efforts to create synergies among the Rio conventions. This dialogue framework can be tasked to develop a coordinated common strategy directly responding to the issues of SDS, considering specific mandates and responsibilities of relevant organizations. In the meantime, the SDS issues should be addressed in political fora at all levels. Stakeholders and policy-makers need the opportunity to debate reliable science and information on SDS to inform decision making and to frame effective policy.

To help further develop and implement this global policy framework, consideration may be given to the creation of a global SDS virtual centre involving SDS-WAS and other UN Agencies, and interested countries and organisations, which may include: (i) a global scientific initiative, (ii) a platform for early warning and resilience, and (ii) a global platform for policy dialogue and coordination.

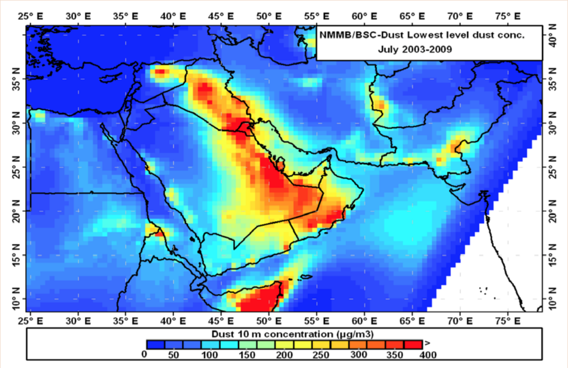
8. Appendix: Case Studies

This section reports case studies of various regional and national actions and studies aimed at monitoring and mitigating SDS.

Box 8.1: Identification of dust sources in the West Asia region

A study was conducted by the Geoinformatic Research Institute (GRI) of the University of Tehran on dust sources in West Asia to support the UNEP-coordinated Action Plan on Dust and Sand Storms for West Asia. The objectives were to (i) identify active dust storm sources in West Asia, (ii) characterize atmospheric patterns that result in dust storms, and (iii) investigate factors that contribute to the formation and intensification of dust storms activities.

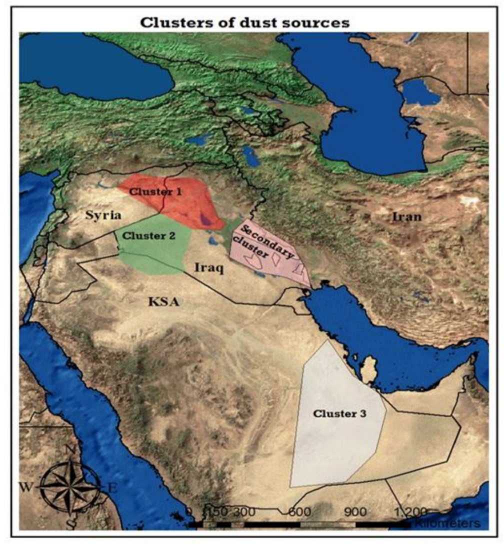
Identification of dust sources was done by determining factors of dust occurrences, using satellite images, atmospheric data, wind trajectory models, soil information, soil water holding capacity, and land cover data. To distinguish dust storms of regional significance from local storms, the following criteria were used to define regional events: (i) storms had to be recorded by at least three weather stations with a minimum distance about 100 km from one another, (ii) observation of widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation (i.e., 06 WMO meteorological codes); (iii) visibility has to be less than 1000 m, and (iv) the storm had to be recorded as independent event.



Dust storm corridor in West Asia. Source: Darvishi Boloorani *et al.* 2014.

Most of the affected regions are located in a corridor stretching across West Asia.

Widespread dust storms were classified, based on the similarity in spatial distribution and atmospheric patterns, in three main clusters and one subsidiary cluster (intensifier). Cluster 1 consists of point sources between the Tigris and Euphrates rivers, stretching from Baghdad in the south to Ceylanpinar in the north and Mosel city in the east (see also Box 8.3). Most activity is in the southern part of the cluster in Iraq, where soil water holding capacity is higher and is therefore more prone to drought compared with the north part in Syria. In addition, the southern part of the cluster is part of the Aljazeera desert, which is prone to erosion due to the natural deposits of salt and sandy alluviums from ephemeral rivers. Dust storm activity corresponds with drought periods and trends in water storage, for example especially during the drought of 2007-2008. Construction of hydraulic structures on the Tigris and Euphrates rivers poses severe risks to water storage downstream, and consequently to vegetation productivity and land susceptibility to dust storms in the future.



Dust storm sources in West Asia, identified as three main clusters and one subsidiary cluster. Source: Darvishi Boloorani *et al.* 2014.

Cluster 2 is located in west and south west Iraq, approximately coinciding with Al-Anbar province. Dust sources relocate towards the south from the northwest of Iraq and the east of Syria (Cluster 1) into the Cluster 2 area and into the north of the Arabian Peninsula, especially in winter and spring. Apart from the north and

Box 8.1: Identification of dust sources in the West Asia region (continued)

plains produces soils that are susceptible to wind erosion. Analysis of atmospheric patterns on dusty days of Cluster 2 indicate considerable cyclone and anti-cyclone weather patterns leading to the creation of high speed winds and consequently dust storm formation.

Cluster 3 is located in east and south east Arabia. This area is bounded by the Rub-al

Khali desert in the south, the Emirates, Qatar and Bahrain in the east, and the Persian Gulf in the north. Dust storms are mostly associated with rare weather events due to the convergence of easterly and westerly winds. Sandy soils constitute 84% of the land coverage resulting in low susceptibility to wind erosion.

The subsidiary cluster is located in southeast Iraq with a small part in southwest Iran. Dust sources in this area are activated simultaneously with other sources, making their dust clouds denser. Although silt soils, which are normally susceptible to wind erosion, cover 43% of the area, these soils have high water holding capacity, which reduces their susceptibility. A combination of drought periods and reduced water flow into marshland, and their over-utilization are contributing factors to increased SDS risk.

The analysis of dominant atmospheric patterns in every cluster shows that generally there are two main patterns favouring dust storms: the summer low pressure of the Iran plateau and cyclonic and anti-cyclonic winter patterns. In common with the situation in many other regions, vegetation reduction, exacerbated by severe drought during the last decade, combined with significant areas of susceptible soils, has led to widespread dust storm formation within the region. Reduced water storage due to upstream water retention was identified as an important additional risk factor in this region.

Dust prognosis in the region could be improved by providing more detailed evidence on dust sources as input to numerical models, including also small-scale hot spots, and their seasonal variability. A start on this was made through the WMO SDS-WAS project "Dust forecast model inter-comparison: Case study of the dust storm over Tehran on 2nd June 2014". This ongoing project, aims to better understand generation and development of small-scale dust storms and explore the potential to use this information to improve dust models so that they can more accurately simulate such events. Work is ongoing with geological survey specialists in the region to collate missing data on dust sources.

Source: Darvishi Boloorani *et al.* 2014.

Box 8.2: Dust storm hot spots in the Islamic Republic of Iran

A study of dust storm hot spots in Iran was conducted by the Geoinformatics Research Institute of the University of Teheran as an initiative to prioritise UNEP pilot study sites under the SDS West Asia Regional Action Plan, and to identify possible interventions.

In 2011, the population of Iran was about 75 million, of whom 71% live in cities. There are large areas of the country with soils that are susceptible to wind erosion. Dust storms have emerged as a significant problem during the last decade, coinciding with droughts, and affecting a large portion of west and southwest Iran. The fertile plain of Khuzestan province is one of the most highly populated regions, which has experienced the largest number of transboundary dust storms during the last decade.

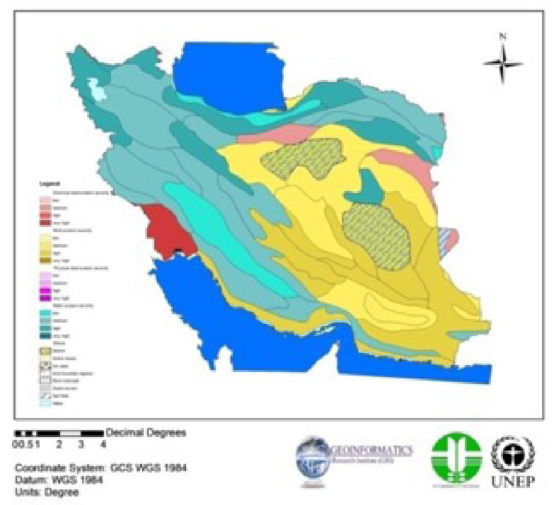
The criteria for selection of hot spot pilot sites included trends in the frequency and severity of dust storm occurrence, representativeness of the ecological conditions and land degradation drivers, and capacity for implementation of interventions. Two main clusters of dust storm activity were identified, representing sources in both arid and humid areas.

In the southwest cluster, more than drought and scarcity of water resources, pressure has come from a population that is three times more than the ecological and pasture potential of the land. This has resulted in deforestation and land use changes, exacerbated by development projects and unsuitable cultivation practices. In the southeast cluster, problems identified included unsuitable cultivation methods, over-grazing and mismanagement of pastures, over-exploitation of woody vegetation, and upstream

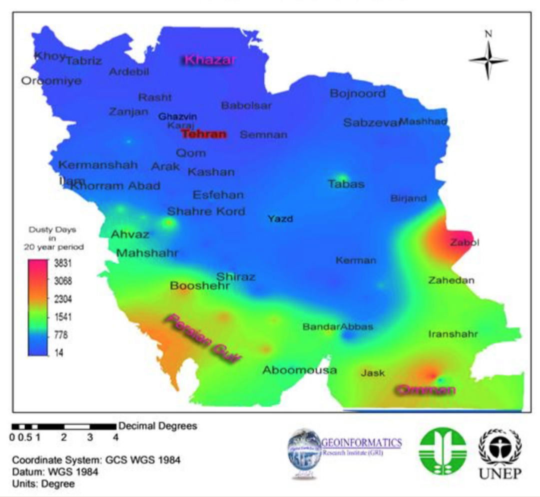
Box 8.2: Dust storm hot spots in the Islamic Republic of Iran (continued)

Interventions identified for pilot sites in the two clusters included developing capacity in sustainable agriculture and natural resources management, use of new energy sources to prevent cutting of trees and shrubs, institutional development, establishing monitoring and early warning systems, and adaptive research on appropriate solutions.

Source: Darvishi Boloorani (2014).

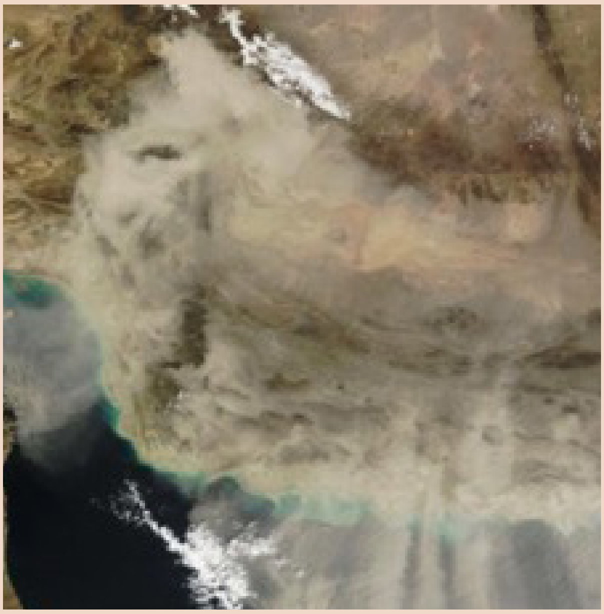


Major land degradation processes in Iran. Yellow areas show wind erosion, with darker colours indicating most severity. Source: Darvishi Boloorani (2014).



Number of dusty days in Iran over a 20-year period from 1985 to 2005 (Mohamadkhan *et al*. 2016)

Two main clusters identified for pilot demonstration projects. Source: Darvishi Boloorani (2014).

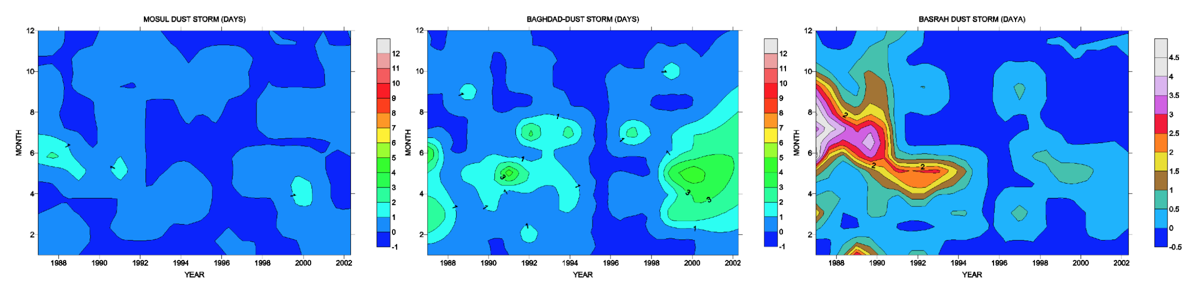


Dust storm over the 2nd cluster identified as a pilot site. MODIS 22 February 2012.

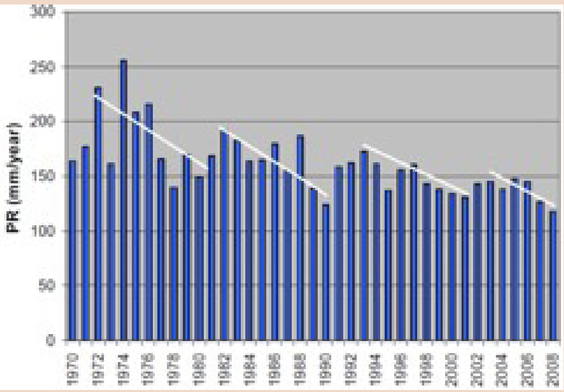
Box 8.3: Identification of dust sources in Iraq using satellite imagery

Dust sources in Iraq were characterized using remote sensing products as part of the West Asia SDS Regional Action Plan. Dust storms are considered to be one of the most important environmental hazards in Iraq and the region.

In the summer, Iraq is affected by low pressure centred in the areas of the Arabian Sea and the Indian Ocean, and the high pressure regions in the plateau of Anatolia, resulting in the Shamal winds in the north and northwest. From mid-June to mid-September this is accompanied by intensive heating of the land surface, causing dust storms to rise to heights of one kilometre. In recent years, the frequency of dust storms has increased in Iraq and the surrounding areas due to drought, causing reduced vegetation cover and deterioration of soil quality. In Mosul, Baghdad and Basra the number of dust storm days increased from 1987 to 2002. There was a surprising increase in the number of dust storms in Baghdad.



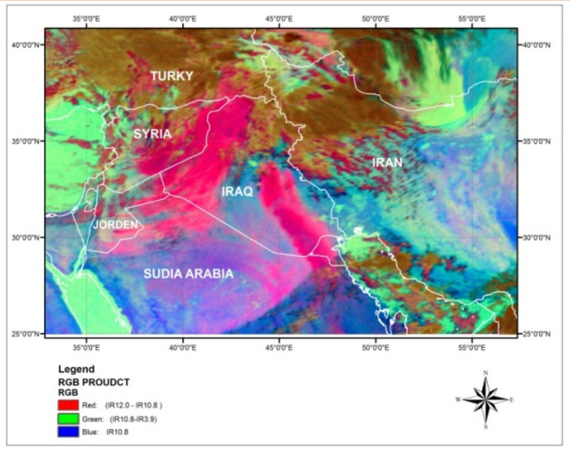
Contour map of dust storms for Mosul, Baghdad and Basra and for the period 1987-2002. Source: Abdulkareem *et al.* 2013.



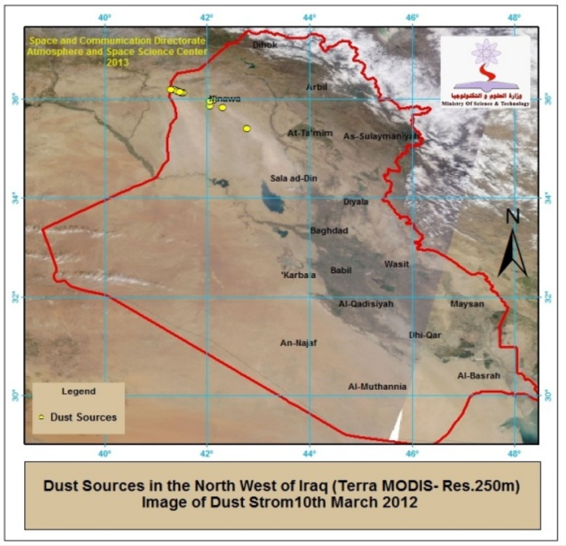
Annual total precipitation rate for Iraq for 1970-2008 showing a trend of decreasing rainfall. Source: Crook 2009.

Various remote sensing products are used to track dust storms and to help to identify their sources. The SEVIRI Meteosat second generation (MSG) images are used to monitor the path and spatial scales of dust storms. Their movement is monitored using true colour composite images supplied by Europe's meteorological satellite agency, EUMETSAT.

The concentration of dust can be observed clearly from true colour red-green-blue (RGB) composites from the Moderate Resolution Imaging Spectroradiometer (MODIS) from the Aqua and Terra satellites. The spatial resolution of 250 metres allows identification of point sources.

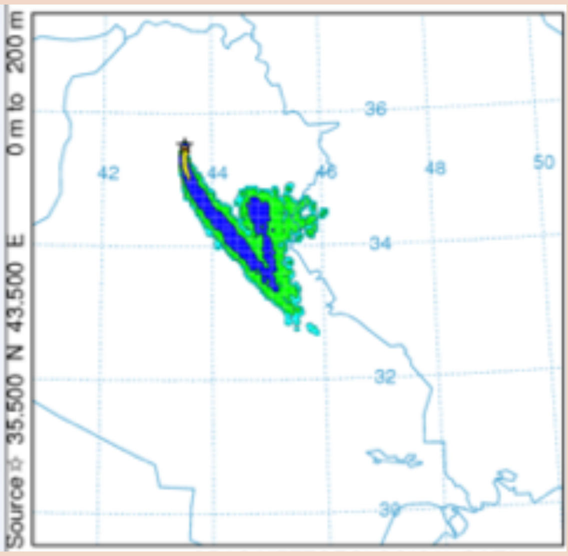


Colour composite image showing a dust storm crossing Iraq on 12 April 2011, computed from archived Meteosat-9 data. Dust appears as magenta colour. Source: Alzubaidi *et al*. 2013.

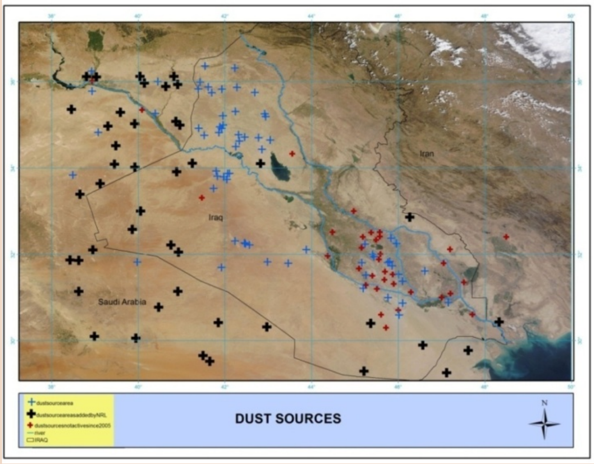


Identification of point sources (yellow dots) of a dust storm on 10 March 2012, using a MODIS colour composite.

Box 8.3: Identification of dust sources in Iraq using satellite imagery (continued)



HYSPLIT output for a dust storm on 3 March 2011 at 1500 UTC .



MODIS image showing passive and active dust sources, produced by the US Naval Research Laboratory (NRL) and the National Oceanic and Atmospheric Administration (NOAA). Blue crosses show dust sources; black crosses show additional dust sources added by NRL; red crosses show dust sources not active since 2005.

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (NOAA-HYSPLIT) is an atmospheric transport and dispersion model. It was developed by the Air Resources Laboratory (ARL) of NOAA. The HYSPLIT trajectory model provides information on simulated smoke plume (and dust) trajectories by tracking a parcel of air that is carried by the mean 3-D wind field derived from a numerical weather prediction model. It is being used to help track the sources of dust storms (Abed *et al.* 2012).

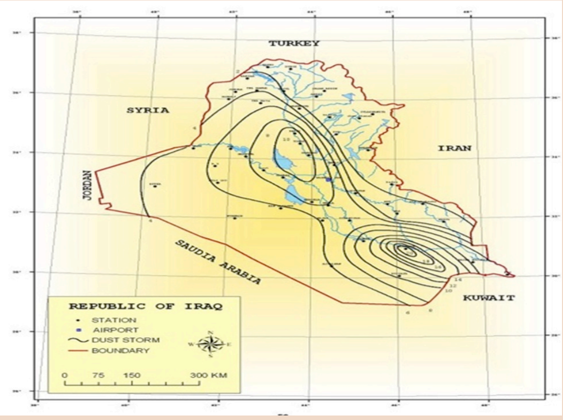
Finally, the different sources of information are combined with a MODIS image to show passive and active dust sources. Further ground investigation is then warranted to deduce the causes.

Source: Abdulkareem A. A. Mohammed, Iraqi Ministry of Science and Technology.

Box 8.4: Assessment of Inorganic and Organic Characteristics of SDS Loads in Iraq

Dust storm distribution

The average annual number of days with dust storms across Iraq for the period 1981 to 2011 indicated that Nasriya was the governorate with the highest frequency of dust storms, reaching 20 days/year.



Average annual number of days of dust storms across Iraq, using monthly means for the period 1981-2011 (Iraqi Meteorological Organization 2013).

Dust characteristics

The composition of dust from storms that reached cities in central and southern Iraq was analysed. The total number of studied dust storms was 48 during 2007- 2010, 7 in 2007, 20 in 2008, 11 in 2009, and 10 in 2010.

Analyses of particle size distributions of dust storms provided information on: clay (20 - 71%, mean=55%), silt (18% - 63%, mean= 32%), and sand (8 - 18%, mean=13%) contents. The main texture of most dust samples was sandy silty clay (71.4%), and to lesser extent sandy clayey silt (28.6%), depending on the energy and velocity of the wind from the regional dust storm.

The following heavy minerals (1.3%) occurred in dust samples: opaque heavy minerals, pyroxene, hornblende, zircon, chlorite, epidote, and garnet. The following light minerals occurred in the dust samples: quartz (52.2 %), feldspar (6.4%), calcite (33%), gypsum (5.6%), and dolomite (1.5%). The roundness of quartz particles ranged from sub-rounded grade (82% of all the studied samples), to rounded grade (18% of all the studied samples), indicating a long distance of transportation.

The mineralogy of the clays in the dust samples were examined by X-ray diffraction (XRD). The clay minerals recognized were: chlorite, illite, montmorillonite, palygorskite, and kaolinite. The presence of palygorskite and kaolinite reflects the arid and semi-arid climatic conditions of the source areas. The presence of chlorite reflects arid and semi-arid conditions in an alkaline environment, while illite minerals are very common in desert soils.

Uranium concentrations (average absorbed dose and average external effective dose) were derived from dust samples of sandstorms from 2-4 July 2009 and 3-4 April 2010 at cities Baghdad and Ramadi. All the results were lower than critical dose level, but the accumulation of the dose from more than one sandstorm may have a damaging effect.

The mean concentration of trace metals in descending order were: Fe (2,940 ppm), Pb (43 ppm), Zn (375 ppm), Ni (154 ppm), Co (90 ppm), Cd (61 ppm), and Cu (56 ppm).

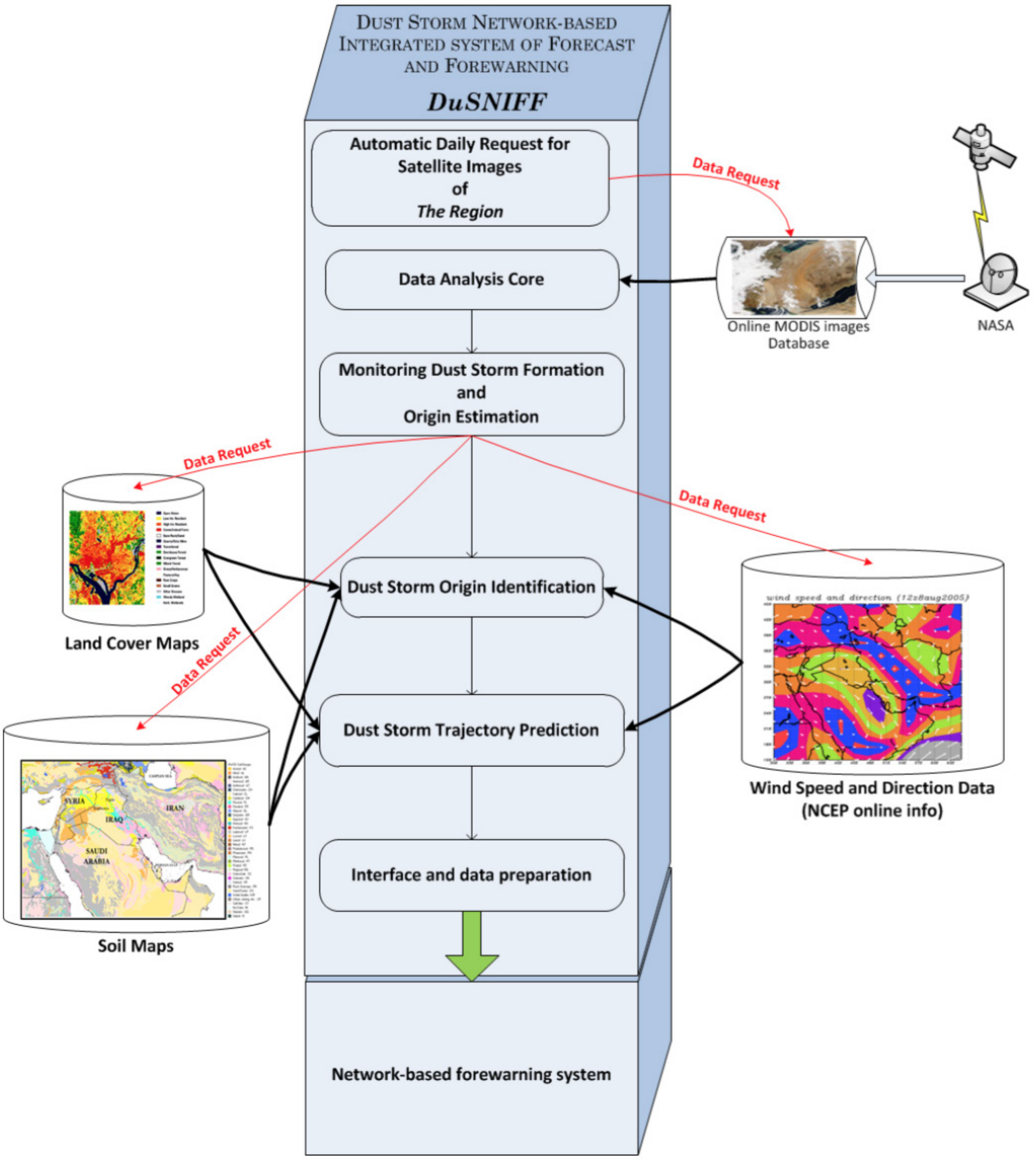
Pollen count frequencies, in descending order, were: Chenopodiaceous (80%), Graminea (68%), Pine (53%), Artemisia (40%), Palmae (18%), Olea (9%), and Typha (3%).

Microorganism frequencies in descending order were: gram-positive *Bacillus* species (49.3 %), *Aspergillus* species (18.6%), *Candida albicans* (10.8%), the gram-negative rods *Escherichia coli* (9.5%), the gram-positive *Cocci streptococcus pneumonia* (8.7%), and the gram-negative rod *Enterobacter Cloacae* (4.4). No viral isolates were found.

Source: Moutaz A. Al-Dabbas, College of Science, University of Baghdad

Box 8.5: Dust storm forecasting for human health - DuSNIFF

Related to the West Asia Regional Action Plan, a Dust Storm Network-based Integrated system of Forecast and Forewarning system (DuSNIFF) is under development at the University of Tehran's Geoinformatics Research Institute (GRI). The system is able to operate at local to regional scales. DuSNIFF can provide information on dust AOD and content analysis, environmental indices, and health impacts, and provide forecasting, early warning, and public announcements.



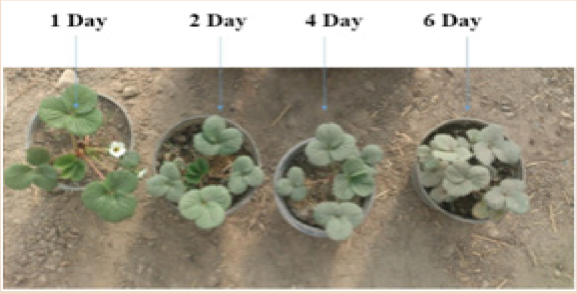
Main components of the DuSNIFF forecast and forewarning system. Source: Geoinformatics Research Institute, University of Teheran.

Box 8.6: Controlled experiments on the impact of dust on plant and animal health

Laboratory experiments are being conducted under controlled conditions in the Islamic Republic of Iran to investigate the effects of dust particles on ornamental plants, crops, trees, and animals, Dust events are simulated using a wind tunnel and dust samples from current active sources in the country.

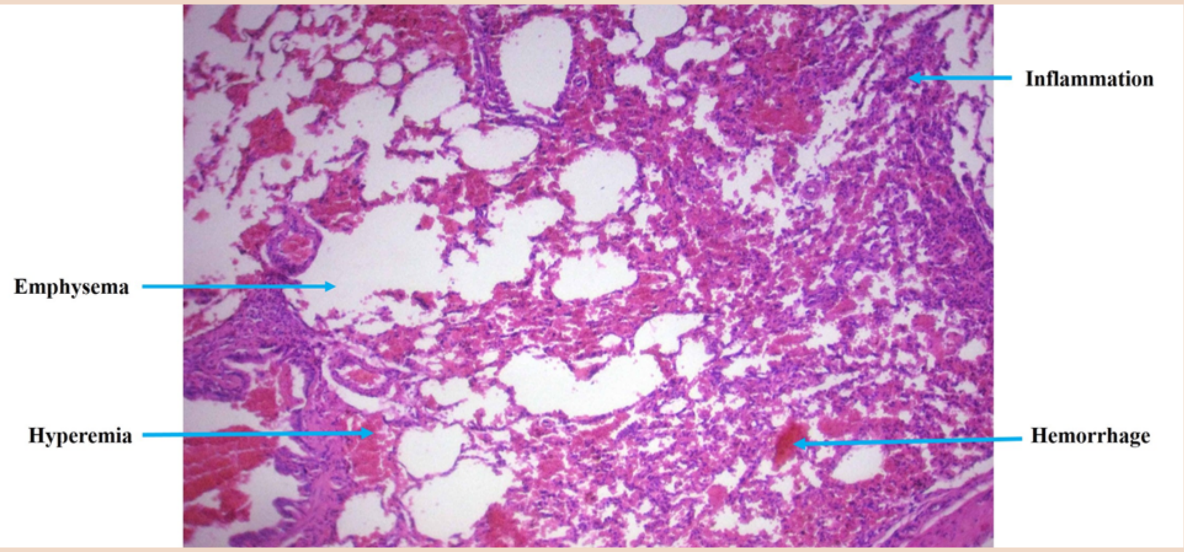
It was found that wheat (*Triticum aestivum*) has a high sensitivity to dust at the tillering stage (early phenological growth stage) compared with at heading stage. West Asia dust storms and especially in Iran tend to occur at the early stages of wheat phenology, having an adverse effect on wheat yield. Leaf chlorophyll, biomass, nitrogen, and moisture content were affected.

Similar results were found in rosemary flower (*Rosmarinus officinalis*), tomato (*Solanum lycopersicum*), marigold (*Calendula persica*), violets (*Viola odorata*), strawberry (*Fragaria ananassa*), and oak seedlings (*Quercus persica*).

	Control	Exposed to Dust (1 to 6 days)
Fragaria ananassa		

Effects of exposure of Fragaria ananassa plants to exposure to simulated dust storms of different periods (1, 2, 4 and 6 days; right) compared with the control (left).

In another experiment two animal species including house mouse (*Mus musculus*) and rat *(Rattus norvegicus*) were exposed to simulated dust storms of different periods and concentration. In terms of lung disease, respiratory epithelium and hyperemia increased in both species. Bleeding (haemorrhage), inflammation and emphysema occurred in rats and pneumonia in house mouse. Edema (accumulation of water in tissue) and fibrosis were not affected by dust levels. Furthermore, dust led to a decrease in the number of white and red blood cells, and levels of alanine aminotransferase, aspartate aminotransferase, and other blood health indicators.

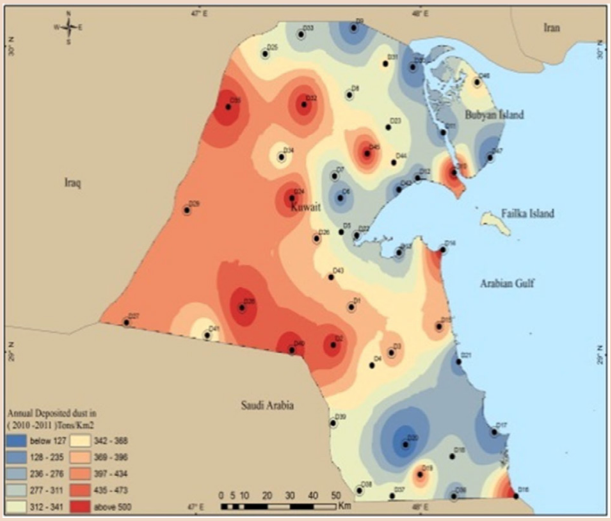


Lung emphysema, hyperemia, hemorrhage and inflammation in rat (*Rattus norvegicus*) exposed to simulated dust storms.

Source: Darvishi Boloorani *et al.* (2015)

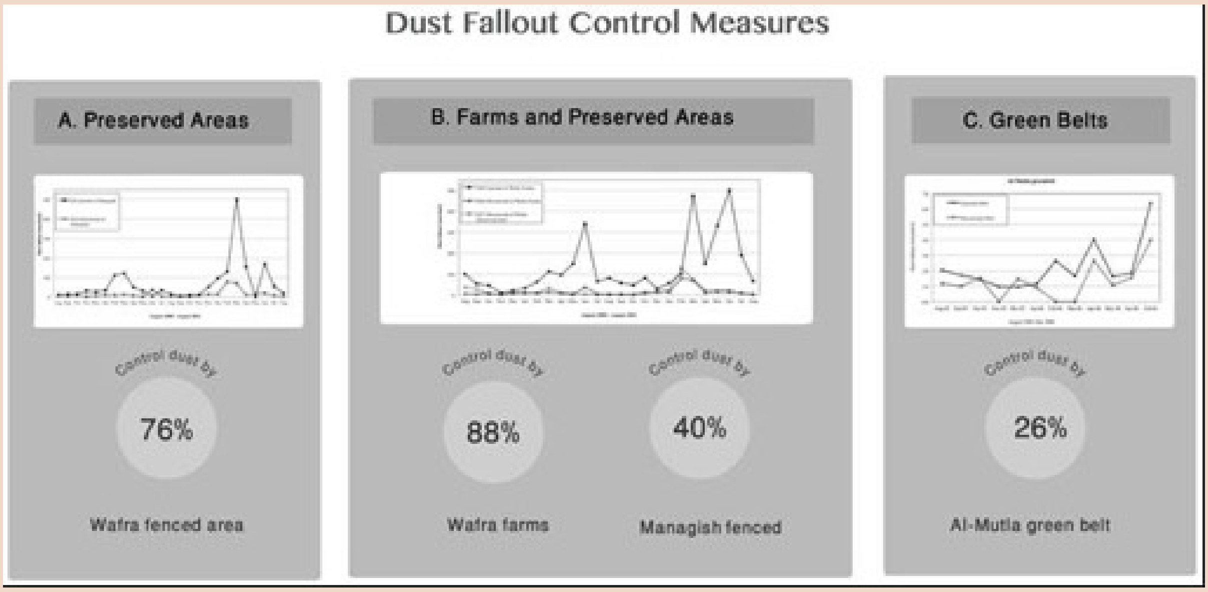
Box 8.7: Impact of preserved areas, farms and green belts on dust deposition in Kuwait.

Kuwait has high depositional rates of dust in its western, southern and northeastern regions as shown in the map below (Al-Dousari *et al.* 2016).



Annual dust fallout in Kuwait 2010-2011

Control measures that have been tested include protected areas of native plants arranged in green belts, consisting of lines of tress of Prosopis and Tamarix species. In two preserved areas dust deposition was 40% to 76% less in downwind areas than in upwind areas. Farm areas reduced deposition by 88%. Green belts reduced dust by 26%. Native vegetation, green belts, and well-managed farms are recommended as the most practical method to mitigate dust problems in the region (Al-Dousari *et al.* in press).



Line plots showing dust deposition rates and reduction percentages (circles) in downwind areas compared to upwind areas for fenced areas (a) farms and fenced areas (b) and green belts (c).

Source: Al-Dousari *et al.* (in press)

Box 8.8: China greening

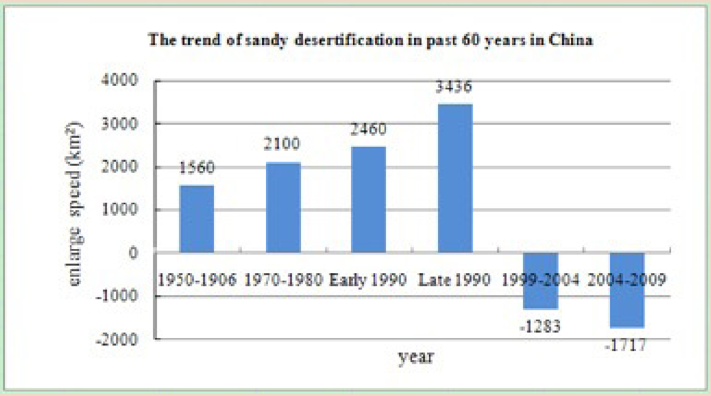
China is one of the countries that is most seriously affected by desertification and SDS. The affected area covers 28% of the total land area and sandy desertification areas have expanded at the rate of 2,460 – 3,436 km^2 annually from 1990 to 2000. There are about 400 million people affected by desertification in China and eco-refugees have appeared in some regions due to desertification. The annual economic cost of desertification in China is estimated at CNY 128.1 billion (USD 19.8 billion), or about 1.4% of Chinese Gross Domestic Product (Tuo and Kebin 2006) and desertification has seriously affected regional economic and social development.

The China National Action Plan (NAP) to Implement the UNCCD was drawn up in 1996 and revised in 2003. China is the first country to setup a national desertification monitoring initiative as a follow-up action. The Desertification Combating Law of China was drafted in 2001. For implementing the UNCCD, various bodies have been established, including: (i) the China National Committee for Implementing the United Nations Convention to Combat Desertification (CCICCD), (ii) the China National Desertification Monitoring Centre, (iii) the China National Training Centre on Combating Desertification, (iv) the China National Research and Development Centre on Combating Desertification, and (v) the Senior Experts Consultant Group in Combating Desertification. Related institutions for combating desertification have been setup in local provinces and autonomous regions.

The well-known programme "Combating Desertification Program in Blown-sand Source Area Around Beijing and Tianjin" and the "Green Great Wall" Programme cover more than 85% of Chinese desertified lands, forming the main body of the effort of the National Combating Desertification Programme.

Desertification monitoring of China consists of national monitoring, key (sensitive) regions and on-site monitoring, desertification project benefit monitoring and sandstorm monitoring. National Desertification Monitoring has been carried out five times since signing the UNCCD. The China Meteorological Administration and State Forestation Administration are jointly in charge of SDS monitoring and forecasting. Many measures, such TV, newspaper, even cell phone message have been used in SDS forecasting and public awareness rising.

After 20 years hard work in combating desertification, the pattern of national desertification has reversed since 2004 and 1,280 – 1,720 km^2 of desertified land has been controlled. As a result, desertification severity has reduced significantly in recent years. This is a significant achievement towards implementing the UNCCD LDN initiative.



Trend of sandy desertification in China over the past 60 years.

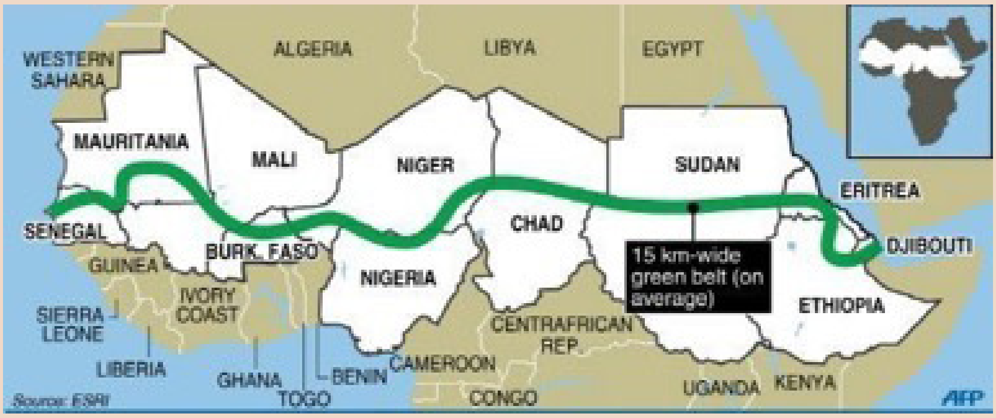
China is moving on with a new vision to extend its greening initiatives along the Silk Route, with an aim to plant 1.3 billion trees in ecologically vulnerable regions over the next 10 years. A Green Silk Road Fund was launched through public-private partnership in China.

Source: SFA (2013)

Box 8.9: The Great Green Wall for the Sahara and the Sahel initiative

Africa is one of the continents most threatened by land degradation and desertification. The Sahara is the world's largest single source of dust emissions and the Sahel is an area at high risk of increased wind erosion and anthropogenic emissions. In order to fight against land degradation, its impacts and to reverse trends, Thomas Sankara, then President of Burkina Faso, proposed the idea to re-green some parts of the Sahel as early as the 1980s. The Great Green Wall for the Sahara and the Sahel initiative was formally adopted at the Conference of Heads of States and Governments of the African Union in January 2007. This strategy was then included in National Action Plans in several Sahelian countries: Burkina Faso, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Sudan, and Chad.

Symbolized by a 15 km wide green belt along 7,775 km from Dakar to Djibouti, designed as a mosaic of sustainable land management interventions, the Great Green Wall is envisioned as a green bulwark in the fight against desertification, wind erosion and SDS impacts.



The location of the planned Africa Great Green Wall.

Thanks to technical and financial mobilisation around the initiative at international and national levels, concrete results have been achieved on the ground as follows:

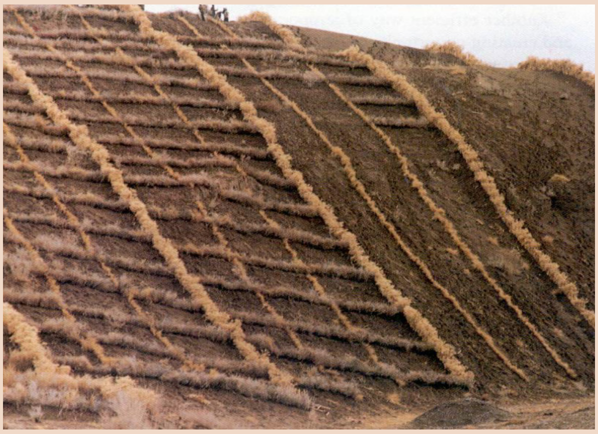
- Ethiopia: 15 million hectares of degraded land restored; land tenure security improved; incentives for communities to participate in land rehabilitation; water catchment improved
- Burkina Faso, Mali, Niger: about 120 communities involved; a green belt created over 2,500 hectares of degraded drylands; and two million seeds and seedlings planted from fifty native species.
- Nigeria: 5 million hectares restored; 319 km of windbreaks set up; 20,000 jobs created. More specifically, in northern Nigeria: 415 km shelterbelt established, 135 ha community woodlot, 235 ha community orchard, and 138 ha community vegetable garden, training over 5,000 farmers in natural regeneration and farm forestry, construction of about 156 solar and wind powered boreholes as sources of water for the affected people and their livestock; engaged over 500 unemployed youths as forest guards and construction of five skill acquisition centres for the training of unemployed youths and women in various livelihood activities
- Senegal 11.4 million trees planted; 1,500 km of firewalls; 10,000 ha using assisted natural regeneration; 24,600 ha of degraded land restored.
- Sudan: 2,000 hectares of land restored.

Source: S. Jaufret, UNCCD Secretariat based on AU (2010); GM (2106); UNCCD (2016b).

Box 8.10: Iranian agreements on sand and dust storms

Title	Date	Place	Major Provisions	Signatory Authorities
Memorandum of Understanding (MOU)	26 Jan 2008	Tehran	8 Paragraphs, Environment and Sustainable Development, a joint committee, workshops.	Iran and Iraq (Ministers)
MOU	5 Jul 2009	Baghdad	6 Articles, sources of dust, new technologies on dust, dust monitoring, training, holding meetings in Baghdad, international cooperation.	Iran and Iraq (Ministers)
Summary Minutes of Negotiations	18 Nov 2009	Tehran	Harmful effects of dust, field visit in Iraq, create a dust monitoring network in Iraq, providing information, air monitoring in the area.	Iran and Iraq (Deputies)
Ministerial Statement Ankara	1 May 2010	Ankara	Establishment of a joint working group, prepared 2-year Plan, exchange of experiences in the field of environment, weather, dust, air quality management, desertification.	Iran, Iraq, Turkey, Syria (Ministers)
Track Record of Implementing Agreements on Combating Dust	6 Aug 2010	Tehran	13 Articles, an operating appendix, dispatch of experts, preparing of credit, training and assisting the Iraqi Meteorological promotion, health management, project shared views on global, regional and sub-regional meetings.	Iran and Iraq (Deputies)
Regional Action Plan	29 Sep 2010	Tehran	10 Articles and appendices, environment and weather and dust, air quality management, desertification and implementation of the action plan.	Iran, Iraq, Turkey, Syria (Ministers)
Bilateral Action Plan	8 Jun 2011	Tehran	10 Articles, an area of 1 million hectares set for desertification operations over 5 years, jointly invested by the private sector, 400-hectare pilot plant operations in Iraq, efforts to reduce the effects of dust, transfer of experiences in the field of desertification and afforestation in Iraq.	Iran and Iraq (Ministers)
Bilateral Action Plan	7 May 2011	Baghdad	10 articles and an appendix on operations, began operations in Iraq desertification.	Iran and Iraq (Deputies)
Executive Document Against Desertification	17 Jun 2011	Ahwaz	7,000 hectares of land desertification began operations in seven provinces in Iraq; rootstock studies on soil, water and vegetation, and meteorology, follow the provisions of the Memorandum of the Special Committee, public education on behalf of the Iraqi government to farmers in sustainable agricultural productivity, land management and watershed management.	Iran and Iraq (Deputies)

Box 8.10: Iranian agreements on sand and dust storms (continued)



SDS remedies in Iran. Top-left: area planted with Haloxylon trees. Top-right: bio-mechanical measures for rain water harvesting and runoff control and seeding. Bottom-left: sand dune fixation.

Source: UNEP (2014).

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10. Acronyms and Abbreviations

AEMET	State Meteorological Agency of Spain
AERONET	Aerosol Robotic Network
ADB	Asian Development Bank
AFOLU	Agriculture, Forestry and Other Land Use
AFR100	African Forest Landscape Restoration Initiative
AI	Aerosol index
APINA	Air Pollution Information Network for Africa
ARL	Air Resources Laboratory of NOAA
ASEAN	Association of Southeast Asian Nations
AVHRR	Advanced Very High Resolution Radiometer
BSC	Barcelona Supercomputing Center
BTD	Brightness Temperature Difference
C-IFS	Composition Integrated Forecast System
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CAMS	Copernicus Atmosphere Monitoring Service
CAHN	Caribbean Aerosol-Health Network
CariCOF	Caribbean Climate Outlook Forum
CARSNET	China Aerosol Remote Sensing Network
CDC	Centers for Disease Control and Prevention
CEN-SAD	Community of Sahel-Saharan States
CGIAR	Consultative Group for International Agricultural Research
CIMH	Caribbean Institute for Meteorology and Hydrology
CMA	China Meteorological Administration
CNY	Chinese Yuan, Renminbi, the currency of China
COMS	Communication, Ocean and Meteorological Satellite of KMA
COP	Conference of the Parties
COPD	Chronic Obstructive Pulmonary Disease
CRAES	Chinese Research Academy of Environmental Sciences
D-HEWS	Dust-Health Early Warning System
DREAM	Dust Regional Atmospheric Model
DSC	Dust surface concentration
DLDD-NEAN	Northeast Asia Network for Desertification, Land Degradation and Drought
DOD	Dust Optical Depth
DRAGI	Dust Retrieval Algorithm from Geostationary Imager
DuSNIFF	Dust Storm Network-based Integrated system of Forecast and Forewarning system
ECMWF	European Centre for Medium-Range Weather Forecasts
EUMETCast	EUMETSAT’s primary dissemination mechanism for the near real-time delivery of satellite data and products
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organization
FENGSHA	Name given to a physical-based dust emission algorithm
FMNR	Farmer Managed Regeneration of Trees
GALION	Global Atmosphere Watch (GAW) Aerosol Lidar Observation Network

GAW	Global Atmosphere Watch programme of WMO
GCM	General Circulation Model
GEMS	Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data project
GFS	Global Forecast System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GMAO	Global Modeling and Assimilation Office of NASA
GOCART	Goddard Chemistry Aerosol Radiation
GRI	Geoinformatics Research Institute of the University of Teheran
GRIMM	GRIMM Technologies Inc
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
IARS	Inertial Altitude Reference System
IASI	Infrared Atmospheric Sounding Interferometer
ICAP	International Cooperative for Aerosol Prediction
IDDI	Infrared Difference Dust Index
IFS	Integrated Forecast System
IMPROVE	Interagency Monitoring of Protected Visual Environments
INDC	Intended Nationally Determined Contribution
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
JMA	Japan Meteorological Administration
KMA	Korea Meteorological Administration
Lidar	Light Detection and Ranging
LPAA	Lima Paris Agenda for Action
MACC	Monitoring Atmospheric Composition and Climate
MASINGAR	Model of Aerosol Species IN the Global AtmospheRe
METAR	Meteorological Terminal Aviation Routine
MERIT	Meningitis Environmental Risk Information Technologies
MODIS	Moderate Resolution Imaging Spectroradiometer, flown on two NASA satellites (Terra and Aqua)
MPLNET	Micro Pulse Lidar Network
MSG	Meteosat Second Generation
MTSAT	Multifunctional Transport Satellites of JMA
NAAPS	Navy Aerosol Analysis and Prediction System
NAP	National Action Plan of the UNCCD
NAQFC	National Air Quality Forecast Capability of NOAA
NASA	The National Aeronautics and Space Administration (NASA) the United States Federal Government responsible for the civilian space programme
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEASPEC	Northeast Asia Sub-regional Program of Environmental Cooperation
NEXRAD	Next-Generation Radar - a network of 160 high-resolution S-band Doppler weather radars operated by the National Weather Service (NWS), an agency of the National Oceanic and Atmospheric Administration (NOAA)
NIER	National Institute of Environmental Research, Republic of Korea
NIES	National Institute of Environmental Studies, Japan

NMHSs	National Meteorological and Hydrological Services
NMMB	Nonhydrostatic Multiscale Meteorological Model on the B grid
NOAA	National Oceanic and Atmospheric Administration of the US
NRL	Naval Research Laboratory of the USA
NRT	Near-real-time
NWS	National Weather Service of the USA
OECS	Organization of Eastern Caribbean States
PAM	Polyacrylamides
PM	Particulate matter
PM10	Particulate matter with an aerodynamic diameter of 10 micrometers or less
PM2.5	Particulate matter with an aerodynamic diameter of 2.5 micrometers or less
PVA	Polyvinylacetate
RAP	Regional Action Programme of the UNCCD
RAPIDC	Regional Air Pollution in Developing Countries
RGB	Red-green-blue
ROK	Republic of Korea
RSMC-ASDF	Regional Specialized Meteorological Centre for Atmospheric Sand and Dust Forecasts
SDG	Sustainable Development Goal
SDS	Sand and dust storms (sand storms and dust storms are defined in Section 2.1)
SDS-WAS	Sand and Dust Storm Warning Advisory and Assessment System established by the World Meteorological Organization
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SLM	Sustainable land management
SRAP	Sub-Regional Action Programme of the UNCCD
SST	Sea Surface Temperature
SW-BAP	Southwest of Buenos Aires Province
SYNOP	Surface synoptic observations
TEMM	Tripartite Environment Ministers Meeting among the Republic of Korea, Peoples Republic of China and Japan
TEOM	Tapered Element Oscillating Microbalance
TJAP	Tripartite Joint Action Plan on Environmental Cooperation
TOMS	Total Ozone Mapping Spectrometer
TPM	Tripartite Presidents Meeting
TPN	Thematic Programme Network of the UNCCD
UKMO	United Kingdom Meteorological Office
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNESCAP	United Nations Economic and Social Commission for Asia and Pacific
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
UNIDSDR	United Nations Office for Disaster Risk Reduction
USDA	United States Department of Agriculture
US EPA	Environmental Protection Agency of the US
WMO	World Meteorological Organization
WOCAT	World Overview of Conservation Approaches and Technologies

WRI	World Resources Institute
WWRP	World Weather Research Programme
XRD	X-ray Diffraction

11. Glossary

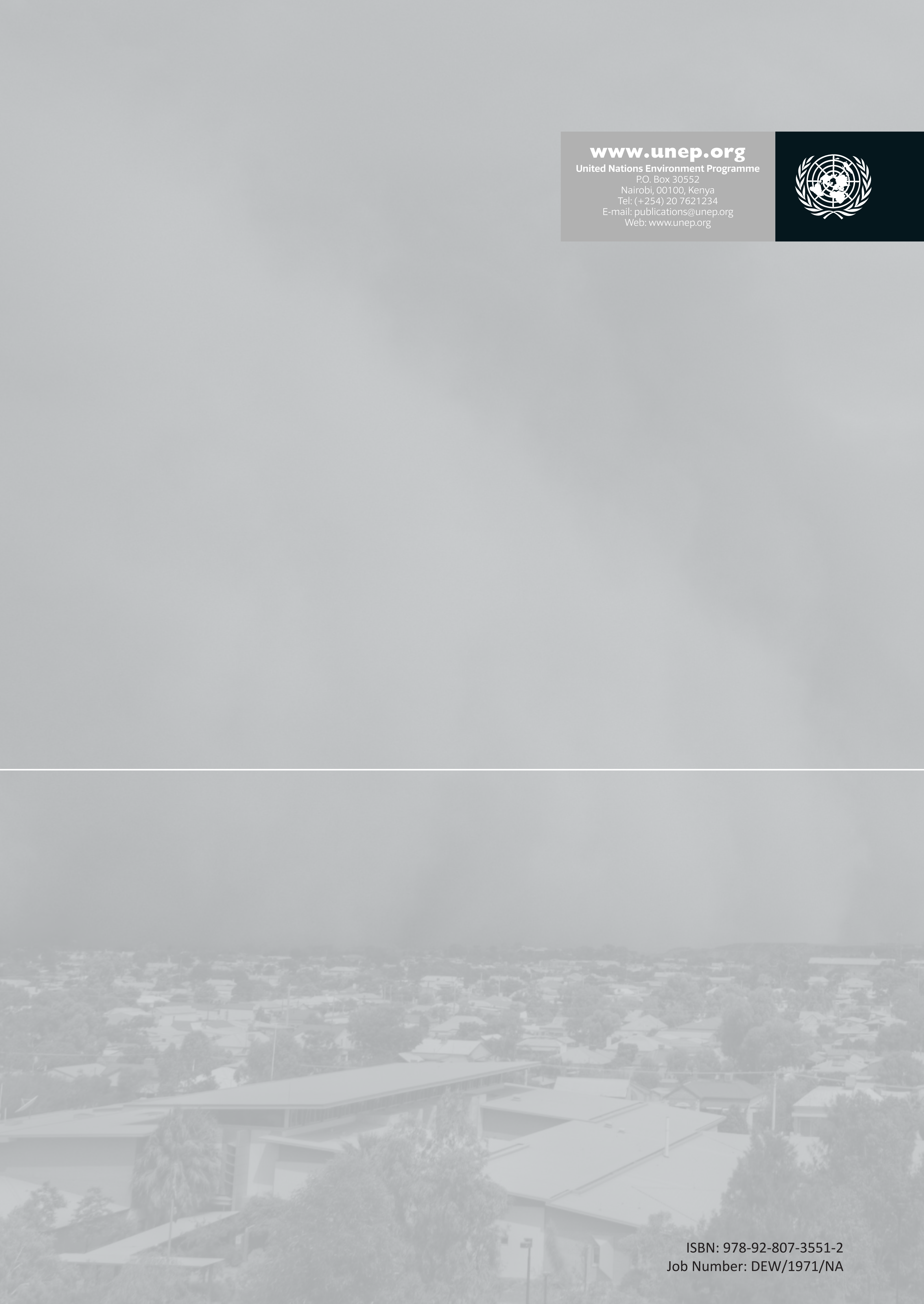
Aeolian	Pertaining to wind activity, especially in relation to wind erosion.
Aerosol	A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 micrometres (µm), that resides in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin.
Aerosol index	An indicator that detects the presence of uv-absorbing aerosols such as dust and soot.
Aerosol Optical Depth	A measure of radiation extinction due to the interaction of radiation with aerosol particles in the atmosphere, primarily due to the processes of scattering and absorption. Also referred to as aerosol optical thickness.
Agroforestry	The intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits.
Albedo	The proportion of the incident light or radiation that is reflected by a surface.
Alkalinity	The accumulation of sodium ions on exchange surfaces of soils, resulting in high pH values and often collapse of soil structure due to dispersion of clays.
Allergic rhinitis	Hay fever, a type of inflammation in the nose which occurs when the immune system overreacts to allergens in the air.
Anthropogenic	As a result of human activity.
Anticyclone	A weather system with high atmospheric pressure at its centre, around which air slowly circulates in a clockwise (northern hemisphere) or counter-clockwise (southern hemisphere) direction. Anticyclones are associated with calm, fine weather.
Aspergillosis	A condition in which certain fungi infect the tissues, especially the lungs.
Biogeochemical cycles	The fluxes of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to water, and from soils to plants.
Biological crusts	Communities of living organisms on the soil surface in arid- and semi-arid ecosystems (e.g., algae, lichens, mosses).
Blowing dust	Dust storm when visibility at eye level is reduced but not to less than 1000 metres.
Ceilometer	A device for measuring and recording the height of clouds.
Cerebrovascular diseases	A group of conditions that affect the circulation of blood to the brain, causing limited or no blood flow to affected areas of the brain.
Chronic Obstructive Pulmonary Disease	The name for a collection of lung diseases including chronic bronchitis, emphysema and chronic obstructive airways disease
Clay	Soil or sediment particles of diameter less than 2 microns.
Coccidioidomycosis	A disease of the lungs and other tissues caused by the fungus Coccidioides, endemic in the warmer, arid regions of the Americas; also known as Valley fever.
Cover cropping	Planting a crop that is primarily to manage soil erosion, soil fertility, soil quality, water, weeds, pests, diseases, biodiversity and wildlife in an agroecosystem
Creep	When particles larger than about 500 microns diameter creep along the land surface under the action of wind.

Cyclone	A system of winds rotating inward to an area of low atmospheric pressure, with a counter-clockwise (northern hemisphere) or clockwise (southern hemisphere) circulation; Cyclones are associated with tropical storms.
Deflation	The removal of loose, fine-grained particles by the turbulent action of the wind.
Desert pavement	A surface layer of closely packed or cemented pebbles or rock fragments from which fine material has been removed by the wind in arid regions.
Desertification	When individual land degradation processes, acting locally, combine to affect large areas of drylands (UNEP 2007).
Distal driver or risk factor	A factor that indirectly acts on or is indirectly associated with a problem. See proximal driver.
Dry deposition	Deposition of dust onto the land surface through natural settling of particles from the atmosphere. See wet deposition.
Dual-pol	Dual-polarized radar technology.
Duricrust	A hard crust that forms at or near the soil surface in semiarid climates as a result of cementation of soil particles.
Dust haze	Dust which resides in the atmosphere from a previous dust storm.
Dust storm	The result of terminal winds raising large quantities of dust into the air and reducing visibility at eye level (1.8 metres) to less than 1000 metres.
Dust whirls	Whirling columns of dust moving with the wind.
Dust bowl	An area of land where vegetation has been lost and soil reduced to dust and eroded, especially as a consequence of drought or unsuitable farming practice.
Earth system	The Earth´s interacting physical, chemical, and biological processes. The system consists of the land, oceans, atmosphere and poles. It includes the planet’s natural cycles — the carbon, water, nitrogen, phosphorus, sulphur and other cycles — and deep Earth processes.
Edema	A condition characterized by an excess of watery fluid collecting in the cavities or tissues of the body.
Emphysema	A condition in which the air sacs of the lungs are damaged and enlarged, causing breathlessness.
Entrainment	The process of particle lifting by the agent of wind erosion.
Ephemeral water body	A water body that dries up periodically.
Erodibility	The inherent yielding or non-resistance of soils and sediments to wind erosion.
Erosivity	A measure of the capacity of wind to cause soil or sediment erosion.
Fetch	The length of unobstructed terrain over which the wind flows.
Fibrosis	The thickening and scarring of connective tissue.
General Circulation Model	A climate model that employs a mathematical model of the general circulation the atmosphere or oceans.
Geosynchronous orbit	A high Earth orbit that allows satellites to match Earth’s rotation.
Haboob	An intense sand storm or dust storm caused by strong winds, often caused by an atmospheric gravity or density current, such as thunderstorm outflow, but can also occur as a result of strong synoptic gradient winds, such as following a dryline or dry frontal passage.
Hydrologic	Associated with water bodies that dry out during some periods, including shorelines, river beds, ephemeral water bodies, and inland water features.

Hydrometeor	An atmospheric phenomenon or entity involving water or water vapour, such as rain or a cloud.
Hyperemia	An excess of blood in the vessels supplying an organ or other part of the body.
Inter-cropping	A multiple cropping practice involving growing two or more crops in proximity.
Ischemic heart disease	Also known as coronary artery disease, a group of diseases that includes: stable angina, unstable angina, myocardial infarction, and sudden cardiac death.
Land Degradation Neutrality	A policy supported by the UNCCD to maintain or improve the amount of healthy and productive land resources over time and in line with national sustainable development. It is incorporated into the Sustainable Development Goal target 15.3.
Lidar	A detection system that works on the principle of radar, but uses light from a laser.
Loess	Sediment formed by the accumulation of wind-blown silt.
Meningococcal Meningitis	A bacterial infection that results in swelling and irritation (inflammation) of the membranes covering the brain and spinal cord; also known as cerebrospinal meningitis.
Micron	A unit of millionth of a metre, or micrometre (μm).
Mineral dust	Atmospheric aerosols originated from the suspension of minerals constituting the soil, being composed of various oxides and carbonates.
Mitigation of climate change	Efforts to reduce or lessen climate change through, for example, reduction in greenhouse gas emissions.
Mitigation of sand and dust storms	Efforts to reduce anthropogenic causes of SDS and to lessen the negative impacts of SDS on human well-being.
Mixed cropping	Growing of different crops on the same field at the same time.
Monsoon	A seasonal prevailing wind in the region of South and Southeast Asia, blowing from the southwest between May and September and bringing rain (the wet monsoon), or from the northeast between October and April (the dry monsoon).
Multistrata systems	An agroforestry system whose components (crops, trees, shrubs, livestock, wildlife, etc.) occupy distinct layers of the vertical structure of the community. An example is the production of coffee intercropped with bananas occupying the lowest strata, shaded by medium-sized fruit trees in the middle vertical strata, with an over-storey of tall timber trees in the upper canopy strata.
Natural ecosystem	An ecosystem that occurs as it would without the influence of human beings. Natural ecosystems include deserts, grasslands, natural forests, lakes, and rivers.
Normalized Vegetation Difference Index	A measure of green vegetation cover calculated from satellite image data.
Nebka	A hillock resulting from accumulation of sand around a shrub or a tree.
Nurse crop	An annual crop used to assist in establishment of a perennial crop.
Ozone	A gas, consisting of inorganic molecules made up of three oxygen atoms, that occurs both in the Earth's upper atmosphere and at ground level. Ozone in the upper atmosphere (stratosphere) plays a beneficial role by absorbing most of the biologically damaging ultraviolet sunlight. On the other hand, high levels ozone at ground level are toxic to living systems.
Paleodata	Data related to the geological past.

Paleolake	An ancient lake that existed in the past when hydrological conditions were different from today.
Pampas	The Pampas are a fertile South American lowland, covering more than 750,000 km^2, which include the Argentine provinces of Buenos Aires, La Pampa, Santa Fe, Entre Ríos and Córdoba; most of Uruguay; and the Brazilian State of Rio Grande do Sul.
Parkland	A land use system consisting of scattered trees in cropland, common across the Sahel.
Pastoralism	The practice of herding or nomadic grazing as the primary economic activity of a society.
Photolysis	The decomposition or separation of molecules by the action of light.
Phytoplankton	Microscopic marine plants. Phytoplankton provide the base of several aquatic food webs.
Planetary boundary layer	The lowest part of the atmosphere that is in regular exchange with the surface in terms of exchange of heat, momentum, water vapour and other atmospheric constituents. Also called the atmospheric boundary layer.
Playa	Flat-bottomed depressions commonly found in interior desert basins and as "sabkhas" adjacent to coasts within arid and semiarid regions; in some locations, these are periodically covered by water to form playa lakes, some of which are saline. Ephemeral, salt, or dry lakes are referred to as playas and playa lakes in North America; salinas, saladas, and salars in South America; chotts (shatts, shotts); sebkhas or sabkhas in the Middle East; boinkas in Australia; pans in southern Africa; or, kavir, or gol in Asia.
Plough pan	A layer of compacted soil just below the plough depth caused by ploughing in wet conditions.
Primary productivity	The rate at which plants and other photosynthetic organisms produce organic compounds in an ecosystem.
Proximal driver or risk factor	A factor that directly acts on or is directly associated with a problem. See distal driver.
Radiative balance	The relationship between the amount of energy reaching the earth and the amount leaving it.
Reduced or no tillage	A practice of minimising soil disturbance and allowing crop residue or stubble to remain on the ground instead of being removed, burned or incorporated into the soil. Reduced tillage practices may progress from reducing the number of tillage passes to stopping tillage completely (no or zero tillage).
Relay cropping	Growing of two or more crops on the same field with the planting of the second crop before the harvest of the first crop.
Respiratory epithelium	A type of epithelium (tissue) found lining the respiratory tract, where it serves to moisten and protect the airways.
Risk	A probability of an adverse.
Risk factor	A factor that raises the probability of an adverse outcome.
Salinization	Accumulation of water-soluble salts in soil.
Saltation	When wind transports particles of between 70 and 500 microns and to a height of less than 1.5 metres above ground level.
Sand	Soil or sediment particles of diameter greater than 63 microns.
Scatterer	A particle that causes electromagnetic waves to scatter (to deviate from a straight trajectory).

Sediment	Naturally occurring material that is broken down by processes of weathering and erosion, and is subsequently transported by the action of wind, water, or ice, and/or by the force of gravity acting on the particles.
Shelter belt	Planting of one or more rows of trees or shrubs planted in such a manner as to provide shelter from the wind and to protect soil from erosion.
Silicosis	Lung fibrosis caused by the inhalation of dust containing silica.
Silt	Soil or sediment particles of diameter greater between 2 and 63 microns.
Soil	The unconsolidated mineral or organic matter on the surface of the earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time. A product-soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics.
Soil conservation contours	The practice of tilling sloping land or leaving strips of lan untilled along lines of consistent elevation in order to conserve rainwater and to reduce soil losses from surface erosion.
Soil cover	The degree to which soil is covered and protected by vegetation, organic litter layers or mulches.
Strip cropping	Growing of different crops in alternate strips to prevent soil erosion.
Surface mulching	Application of a layer of material (usually organic residues) to the surface of an area of soil.
Surface roughness	Character of a surface that produces drag on wind; results in turbulent flow with efficient transfer of matter and energy.
Suspension	Suspension of particles of diameter of less than 70 microns in air.
Sustainable land management	Practices and technologies that aim to integrate the management of land, water, biodiversity, and other environmental resources to meet human needs while ensuring the long-term sustainability of ecosystem services and livelihoods.
Synoptic meteorological conditions	An overview of weather conditions at a specific time.
Tailing dumps	Materials left over after the process of separating the valuable fraction from the uneconomic fraction of a mined material, or mine dumps.
Trace gas	A gas that makes up less than 1% by volume of the Earth's atmosphere, and includes all gases except nitrogen and oxygen
Tracheitis	Inflammation of the trachea.
Tropospheric	The lowest layer of Earth's atmosphere and site of weather.
Value chain	The process or activities by which a company adds value to an article, including production, marketing, and the provision of after-sales service.
Wadi	A channel that is dry except in the rainy season.
Wet deposition	Deposition of dust onto the land surface in precipitation. See dry deposition.



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