8. Sand and dust storm source mapping

Chapter overview

This chapter provides extensive details on how to map potential sand and dust storm (SDS) source areas based on the nature of the soil. The chapter covers drivers of SDS source activity, anthropogenic sources, the distribution of SDS sources and two approaches to SDS source mapping. The chapter includes a process for high-resolution SDS source mapping based on soil and surface data, provides formulae for this type of analysis and includes a list describing data sources which can be used in the SDS source mapping process. This chapter is to be read in conjunction with chapter 2.

8.1. Overview of the physical sources of SDS

Based on the information compiled from Lu and Shao (2001), Shao (2008) and United Nations Environment Programme (UNEP), World Meteorological Organization (WMO) and United Nations Convention to Combat Desertification (UNCCD) (2016), the primary source of sand and dust storms (SDS) can be defined as “a bare topsoil surface susceptible to wind erosion or any surface capable of emitting soil particles in favourable wind conditions”. “Bare topsoil” is a soil surface fraction without vegetation or snow/ice cover or that is covered by a water body (for example, a lake, river or wetland).

A soil surface is susceptible to wind erosion when it contains smaller soil particles, generally clay and silt size particles up to about 50–60µm in diameter, depending on the classification system (Schaetzl and Anderson, 2009). In case of high surface wind velocity, sand size particles (predominantly very fine sand of up to about 100 µm in diameter) may be emitted from a surface and carried away, but over much shorter distances than finer particles.

The likelihood of soil becoming part of an SDS event is increased if the soil structure is disturbed and loose, leading to particles being free for uptake by wind. Other conditions that can contribute to soil becoming part of an SDS event include:

- low topsoil moisture
- the soil not being frozen
- surface wind velocity above a certain threshold closely related to particle size distribution in topsoil and topsoil moisture (see **chapter 2**)

SDS source locations and conditions are distinguished by the nature of the source:

- **Permanent SDS sources** are mostly located in desert areas and are constantly susceptible to wind erosion given their fine (small µm) topsoil content, permanent warm and arid climate, no or limited vegetation cover and the general absence of water bodies.
- **Dynamic SDS sources** can change in the level of SDS-related activity depending on the season, weather conditions and human impacts.

The dynamics of SDS sources are related to seasonal changes in the vegetation cover, snow cover, the existence of or changes in the extent of water bodies and whether the soil is frozen. These variations create notable changes in SDS source geographic distribution.

Dynamic SDS sources range from “seasonal” to “occasional”. “Seasonal” sources are usually controlled by climatological seasonality in weather conditions and “occasional” sources are the ones not necessarily active during favourable seasonal conditions, but which require an additional driver to trigger their activity, usually extreme weather and/or direct human impacts. SDS sources may evolve into sources with different temporal activity, meaning they may change from occasional to seasonal or permanent, or vice versa, depending on the impacts of drivers of SDS source activity. Determining the likelihood of such behaviour requires regular monitoring of SDS sources.

Drought, as an extreme seasonal or multi-season weather condition, may lead to SDS or an increase in SDS activity. Heat waves may prevent freezing of topsoil and contribute to increased SDS activity. For additional details on permanent and dynamic sources, see Kim et al. (2013), Vukovic et al. (2014), Tegen (2016), WMO and UNEP (2013) and UNEP, WMO and UNCCD (2016).

Human interventions can have positive or negative impacts on SDS source activity. Sustainable land management practices, such as afforestation and climate smart agriculture (Sanz et al. 2017), may reduce the likelihood of SDS (**see chapter 12 and 8.3**).

On the other hand, anthropogenic impacts that can induce and increase vulnerability of topsoil to wind erosion come from different sectors of the economy and include direct and indirect impacts. This is discussed further in **chapter 8.3**.

Identifying and mapping SDS sources, and understanding why these locations produce SDS, provides information for SDS risk and impact assessment, SDS mitigation planning, SDS forecasting and establishment of SDS early warning systems (WMO and UNEP, 2013) (see **chapters 5, 6, 7, 9, 10, 11** and **12**). Mapping the spatial and temporal distribution of SDS sources requires:

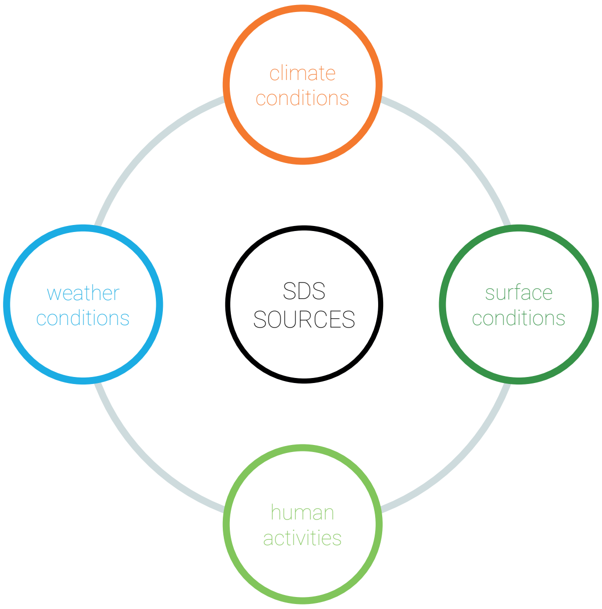
- understanding what causes the formation and activation of SDS sources (see **chapter 8.2**)
- defining parameters for SDS productive areas (see **chapter 8.2**).
- understanding ways to adjust SDS mapping procedures to provide useful information

A proposed methodology to detect the surface potential for SDS formation is described in **chapter 8.5**.

8.2. Drivers of SDS source activity

Four drivers impact the existence of SDS sources, as summarized in **Figure 22** and discussed herein. Each driver interacts with each of the other drivers. This interaction can vary in time and space and may lead to an increase or decrease in SDS generation. **Climate conditions:** Climate is one of the main drivers of the formation of permanent SDS sources in desert areas (Shao 2008; Shao et al., 2011).

Figure 22. Drivers that impact sand and dust storm activity



Extreme aridity, together with high winds in desert areas with insufficient vegetation and long-term exposure to erosion, can lead to the formation of SDS sources. Climate conditions also affect seasonal activity of SDS sources, which is related to seasonal change of surface conditions – mainly of vegetation cover – and seasonal winds (Kim et al., 2013; Tegen, 2016).

Weather conditions: Weather conditions can induce additional SDS source activity and lead to the formation of new SDS sources. Consistent or repetitive dry weather conditions with seasonal wind patterns is distinguished as a separate driver from climate conditions. At the same time, changes from usual SDS source behaviour can be the result of extreme weather conditions, which become more common in a world where the climate is constantly changing (Intergovernmental Panel on Climate Change [IPCC], 2012; 2014a). Meteorological drought is an example of extreme weather and can cause increased SDS source activity.

However, the true effect of drought also depends on other drivers (**Figure 22**) which can amplify or reduce the impact of drought. In mid- and higher latitudes heat waves may trigger the activity of SDS sources during the season when the surface is usually frozen or covered by snow. This effect is expected to increase in the future under the changing climate conditions.

Wind speeds which vary from usual seasonal atmospheric circulation are also an element in the weather driver package. For example, during extreme surface heating or intense cold frontal movement, formation of strong convective activity is possible. This can produce cold downdrafts from clouds and, consequently, high surface winds that increase SDS source activity in the event of low humidity conditions (Knippertz et al., 2009; Knippertz and Todd, 2012; Vukovic et al., 2014). Terms associated with such events are "haboob", "line of instability", "cold pool" and "density currents".

Surface conditions: Surface conditions are soil characteristics (most importantly soil texture and structure), soil condition (moisture and temperature), and land cover (bare soil fraction). Soil texture with a fine particle content is a precondition for a location becoming an SDS source. If soil structure is disturbed, topsoil particles are more susceptible to wind erosion where soil moisture is low and soil temperature is above freezing (Kok, 2011; Kim et al., 2013; Wu et al., 2018). Bare soil surface is a precondition for the existence of active SDS sources, which means there is no vegetation, snow/ice or water on the topsoil. Areas that include fractions of bare soil surface, like sparsely vegetated area, are considered as SDS sources, with less possibility of dust emission compared to fully bare land areas.

Due to the complexity of the ways surface conditions and soil surfaces respond to other drivers, and their large spatial and temporal variability (including many unknown processes), it is better to distinguish surface conditions as a separate driver. Expanding knowledge of soil composition can strongly contribute to understanding of these interactions, as well as the understanding of SDS impacts on humans and the environment (Nickovic et al., 2012; 2013; Sprigg et al., 2014).

Human activities: Interaction of humans with natural processes can lead to amplification or suppression of other drivers.

Direct impacts of human activities include change of surface conditions. Water scarcity, tillage, grazing and deforestation can have a direct impact on soil degradation (Orr et al., 2017) and thereby result in the amplification of SDS source activity. Sustainable land management practices (Sanz et al., 2017; Orr et al., 2017) can reduce SDS activity. Indirect impacts of humans on SDS activity include the anthropogenic impact on the climate which affects the other drivers of SDS source activity.

Human activities are a significant driver for changes in the whole climate system, with increasing world population and global warming currently the two largest stressors for the environment. The human impact is measured as a planetary-scale geological force (Diffenbaugh and Field, 2013; Steffen et al., 2015; Cherlet et al., 2018). This is the reason for separate analysis of SDS sources, which exist mainly as a consequence of human activities, as described in **chapter 8.3**.

8.3. Anthropogenic sources

Human activities have a significant impact on the climate system (IPCC, 2014b) and especially on land surface characteristics by transforming them to surfaces suitable for food production and other economy benefits (IPCC, 2019).

These activities can impact SDS source formation and increase the activity of dynamic SDS sources, possibly transforming them into permanent source areas (UNEP, WMO and UNCCD 2016; United Nations Economic and Social Commission for Asia and the Pacific [UN ESCAP], 2018). Enhanced emissions can cause severe negative impacts on the environment, human health and safety (Pauley, Baker and Barker et al., 1996; Arizona Department of Environmental Quality, 2012; Sprigg et al., 2014; Irfan et al., 2017).

When human activities are the predominant driver of SDS source activity, these SDS sources are called “anthropogenic sources”. The human activities which contribute to anthropogenic sources occur in multiple sectors, including agriculture, water, forestry, energy and transport. Anthropogenic sources can result in “direct” and “indirect” impacts. Factors with “direct impacts” that have the most effect on SDS source activity are:

- land cover changes, disturbance of the topsoil and loss of soil structure, which are mostly the consequence of agriculture practices (tillage and livestock breeding).
- use of water for irrigation, hygienic needs (especially for large urban areas) and industry.
- other factors that can dominate impact in some regions, such as deforestation, fires, mining.

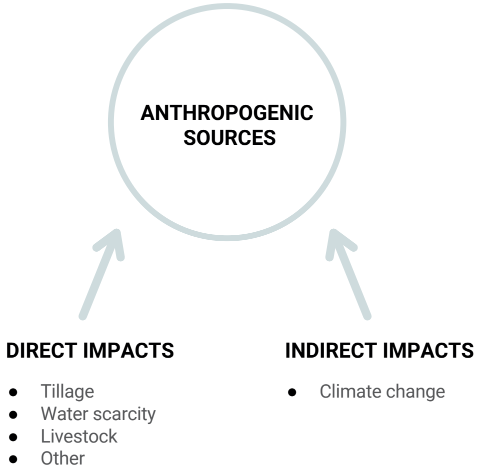


Figure 23. Most relevant human impacts leading to sand and dust storm anthropogenic sources

Human activity-related climate change has an impact on an increased frequency and intensity of severe weather events, like drought, fires and high winds, and thereby can have “indirect impact” on SDS source activity (IPCC 2012; 2014a). The most important impacts which lead to the formation of anthropogenic sources are shown in **Figure 23**.

Recognizing and acknowledging the human impact on SDS source activity and understanding the impact of SDS generated from anthropogenic sources is important for SDS source mitigation planning and implementation. Prioritizing mitigation of anthropogenic sources considers restoration of the natural dust cycle in the climate system and achieving land degradation neutrality. Assessment of climate change impact on SDS source activity contributes to adaptation planning in areas vulnerable to SDS.

8.4. Distribution of SDS sources

Knowledge on SDS source distribution is an initial step for assessment of risk and impact of SDS and implementation of SDS source mitigation measures. Distribution and patterns of dust sources are complex and have high spatial and temporal variability, which is the consequence of the high spatial variability of topsoil texture and structure, land-use, socioeconomic impacts and variability of climate and weather conditions.

Spatial scales of SDS sources range from large-scale erodible areas in desert regions to point-like sources usually sensitive to agriculture practice and water scarcity (Shao et al., 2011; Lee et al., 2009 ; Ginoux et al., 2012; Vukovic et al., 2014), as well as the retreat of glaciers and occurrence of high-latitude SDS events (Bullard et al., 2016; Arnalds, Dagsson-Waldhauserova and Ólafsson, 2016). A dense pattern of point-like sources may individually emit dust plumes that merge into a larger-scale SDS event, which may reach the significance of emissions from large-scale sources.

Areas and locations that have the best conditions (drivers) for SDS generation and that produce a major share of airborne sand and dust concentrations are called "hotspots" (Engelstaedter and Washington, 2007). This type of source is usually:

- small in scale and situated in larger-scale SDS productive areas (Lary et al., 2015; Feuerstein and Schepanski, 2019), or
- distributed as individual sources outside desert areas (Lee et al., 2003; Arnalds, Dagsson-Waldhauserova and Ólafsson, 2016).

The global and regional distribution of major SDS source areas has been covered in detail in several reports, including WMO and UNEP (2013) and UNEP, WMO and UNCCD (2016). The main SDS productive source areas are situated in the desert belt in the northern hemisphere (Central Asia, the Middle East, North Africa). Other notable SDS productive areas are in south-west part of the United States of America (USA), the southern part of South America, south Africa and Australia. See **chapter 2** for more information on SDS source areas.

8.5. SDS source mapping

8.5.1. Two approaches to detecting SDS source areas

Understanding where to implement SDS source reduction actions requires knowing where SDS can originate and how sand and dust can be entrained into SDS events (Middleton and Kang, 2017). Two major factors that influence the generation of SDS are high surface winds and a free-soil surface.

High surface wind velocity can be a consequence of seasonal patterns of large-scale atmospheric circulation and/or extreme local weather conditions (see **chapter 8.2**). A "free-soil surface" is relatively dry, unprotected topsoil (free of vegetation, snow, ice or water), which is not frozen, the soil particles of which are free to be emitted under windy conditions. As surface winds of sufficient velocity for soil particle emission are common in all parts of the world, SDS generation is determined in a significant way by the existence of a free-soil surface.

SDS source mapping can be divided into two approaches:

1. SDS source mapping from data on SDS occurrence
2. SDS source mapping from data on surface conditions

These two approaches are discussed as follows.

8.5.2. Sand and dust storm source mapping based on sand and dust storm occurrence

SDS source mapping based on SDS occurrence uses data on SDS occurrence, such as satellite data, ground PM measurements and visibility data (Wang, 2015). Results are better if longer periods of data are included in the analysis.

Global distribution of SDS sources obtained using this approach can be found in Shao (2008), Shao et al. (2011) and Ginoux et al. (2012). Remotely-sensed data and machine learning can generate relatively high-resolution point-like sources (Lary et al., 2015). The advantages and disadvantages of mapping based on data on SDS occurrence are listed in **Table 18**.

Table 18. Advantages and disadvantages of sand and dust storm mapping using sand and dust storm occurrence

Advantages	Disadvantages
• Good representation (high confidence) of synoptic overview of major and frequently active sand and dust storm (SDS) sources (permanent and seasonal). • Recognize global and regional sources that are dominant in SDS generation.	• It represents mapping of SDS activity (or occurrence), not SDS sources. • Spatial and temporal coverage of SDS observations is not continuous. • Resolution is lower than mapping resolutions of other soil surface related parameters. • Unable to recognize/delineate many of small-scale and, occasionally, active SDS events. • Climatological approach (averaging of long-term data) gives advantage to natural (permanent and seasonal) and/or larger scale SDS sources. • Underestimates SDS sources which are small scale and/or not frequently active.

8.5.3. SDS source mapping of data on soil surface condition

This approach to SDS source mapping uses a combination of data on the potential for the soil surface to emit soil particles which can be carried away from source in favourable wind conditions, that is, the soil surface's susceptibility to wind erosion.

The approach is based on use of soil and surface data to estimate (parameterize) information on soil surface potential to produce SDS, rather than to detect SDS occurrence.

The SDS source mapping based on soil conditions is used, for example, in mapping SDS sources in numerical modelling of dust transport (Nickovic et al., 2001; Kim et al., 2013; Vukovic et al., 2014), and in studies that investigate the level of land degradation and desertification (UNCCD, 2017; Cherlet et al., 2018). This approach to SDS source mapping is less used due to its complexity.

However, the approach can significantly contribute towards the better definition of SDS source patterns, including their small-scale features, which is necessary in planning actions related to SDS source mitigation. Advantages and disadvantages of mapping based on data on soil surface conditions are listed in **Table 19**.

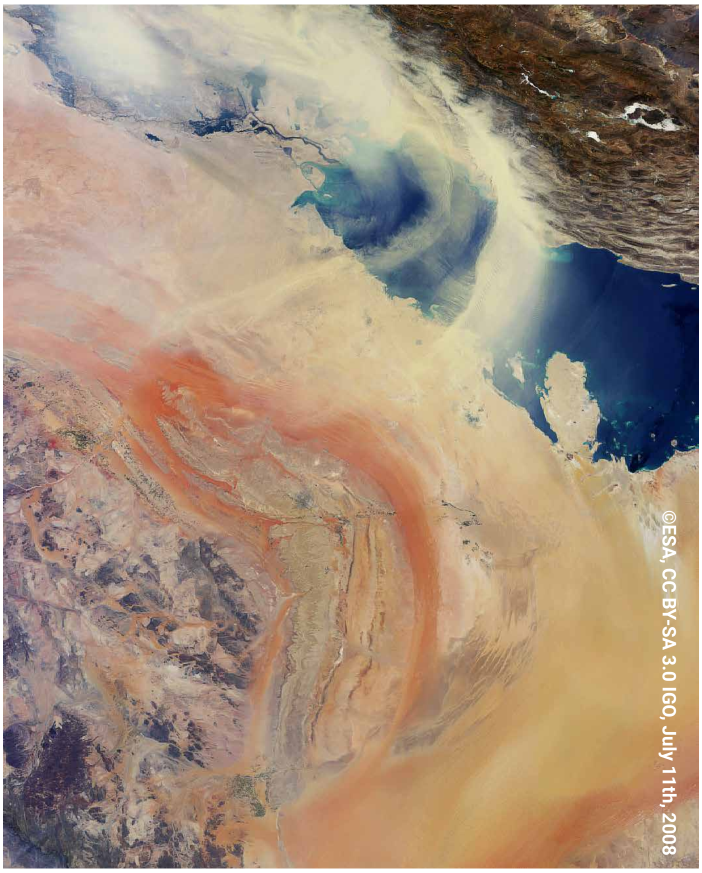


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Table 19. Advantages and disadvantages of sand and dust storm mapping based on soil conditions

Advantages	Disadvantages
▪ Contains data on soil characteristics and land-use. ▪ Can provide high-resolution SDS source patterns. ▪ Can detect/delineate small-scale sources and distinguish SDS source hotspots. ▪ Can detect surfaces with high potential for SDS generation in extreme weather conditions, even if they are not frequently active.	▪ Requires a relatively complex combination of information from different sources of data. ▪ Due to high spatial variability and insufficient soil sampling, the quality of soil information may be low, which requires implementation of additional information. ▪ Does not include information on frequency of SDS generation.

Information on SDS sources based on SDS observations can be used to verify the reliability of data obtained from surface observations over larger SDS source regions. A good – and relatively simple – example of this methodology is SDS source mapping using topography data which is verified using satellite data, found in Ginoux et al. (2001), and later improved with seasonal SDS source change, found in Kim et al. (2013).

Overcoming the disadvantages of this approach involves:

- acquiring more accurate national data
- additional national observations and data sets
- methodologies that enable even higher resolution mapping.

A basic methodology for SDS source mapping using surface data, with possible map upgrades depending on data availability and quality, is discussed in more detail in **chapter 8.6**.

8.5.4. Gridded data on SDS sources

“SDS source mapping” means representation of geo-referenced data on SDS sources on a regular grid with certain resolution, where one number represents information about the SDS source in a grid box with dimensions that depend on the map resolution. Usually, information on the SDS source is scaled to have values from 0 to 1 (where 0 is no SDS source in the grid box and 1 is the whole area in the grid box being fully SDS-productive and/or have highest potential for SDS generation) or in percentage terms (0–100%).

Depending on the approach used for SDS source mapping, the data obtained can have different meanings.

1. When SDS source mapping is done using data on SDS occurrence (Prospero et al., 2002; Walker et al., 2009; Ginoux et al., 2012; Akhlaq et al., 2012; Shao et al., 2013; Division of Earth & Ecosystem Sciences, 2013; Sinclair and Jones, 2017), gridded information on SDS sources is usually derived from the frequency of SDS detection. Thereby, this kind of map represents frequency of SDS activity, assuming that areas with the highest frequency are the strongest sources of SDS, which corresponds to close to one in the SDS source map. In this case, SDS source hotspots are areas with the highest frequency of SDS occurrences.
2. When SDS source mapping is carried out using data on soil surface conditions, gridded information on SDS sources represent the potential of the soil surface in the grid box to emit particles in the event of high wind conditions. Thereby, this kind of map represents a fraction of the free-soil surface in the grid box. Values closer to one represent areas that are highly susceptible to wind erosion in cases of high surface velocity winds. In this case, SDS source hotspots are the surfaces with higher potential for emission of particles.

On climate scales, areas with the most frequent SDS occurrences will coincide, in a large part of the world, with areas with the highest potential for SDS generation. Because of their dynamic component caused by the change in SDS source drivers (see **chapter 8.2**), over larger timescales, SDS source map patterns can be significantly different, especially during extreme weather events that can trigger the activation of SDS source hotspots.

Such SDS sources can have low frequency of activity and are could possibly not be recognized as hotspots in the mapping approach that uses data on SDS occurrence, but must be recognized as having a high potential for SDS generation in mapping approaches that use data on surface conditions. For this reason, and due to direct and indirect human impacts on SDS formation (see **chapter 8.3**), mapping of SDS sources for the purpose of mitigation planning, forecasting of SDS and early warning systems, should consider applying a methodology based on soil surface data.

8.6. Methodology for high-resolution SDS source mapping

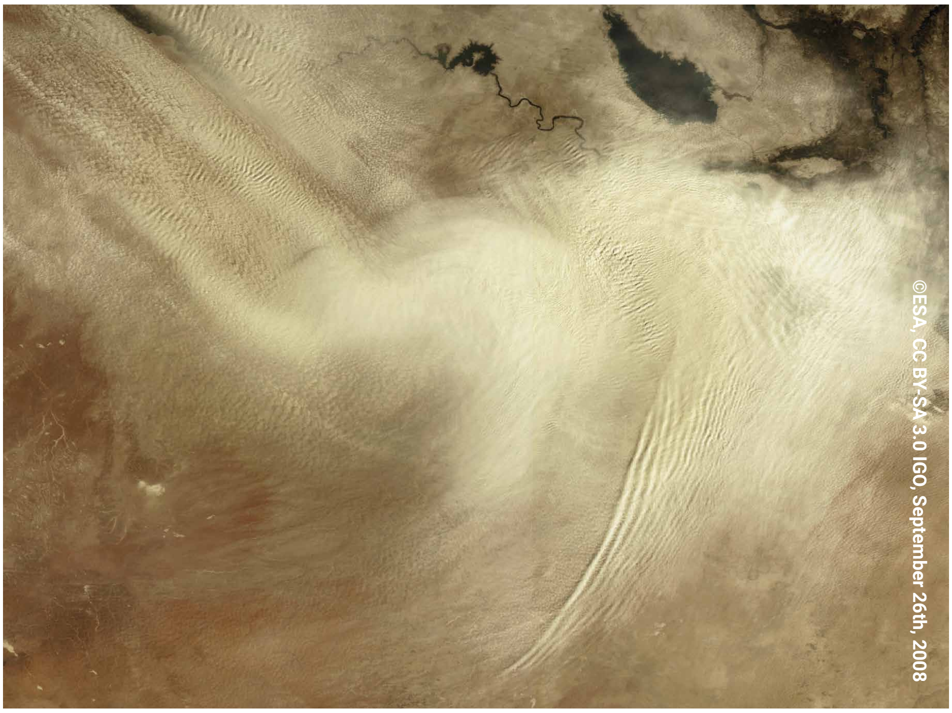
This section explains a methodology that enables high-resolution SDS source mapping, which relies on the approach discussed in **chapter 8.5.2**. It is based on available global data, which may be supplemented or replaced with national data of higher accuracy and resolution, if available, or may be supplemented with additional information available on national level, like SDS source hotspots.

8.6.1. Clusters of relevant data

Implementation of a methodology based on soil surface data analysis is necessary to achieve high-resolution SDS source mapping (at a 1 km or higher level of detail) which includes all areas that have the potential to generate SDS in favourable wind conditions.

A list of basic (most important) parameters that are required in SDS source mapping is presented in **Figure 24**. These parameters represent clusters of data sets, which are combined using certain criteria, mainly based on setting threshold values that serve the purpose of eliminating non-productive areas from the global land surface.

Therefore, this approach to SDS source mapping may be understood as an elimination method – excluding areas that are certainly not SDS-productive. The remaining areas represent potentially SDS-productive surfaces, which should include all permanent and dynamic (seasonal and occasional) sources.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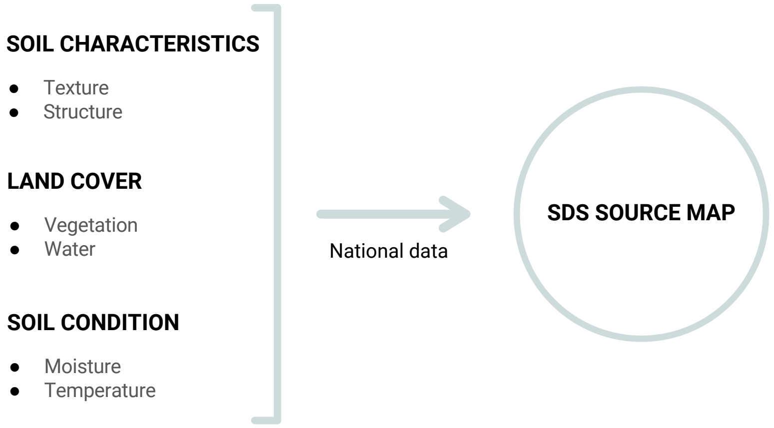

Figure 24. Soil surface parameters necessary for sand and dust storm source mapping

Note: Use of national data, if available, can improve the result of SDS source mapping at subnational and national scales, based on global data sets.

An initial cluster of parameters that are necessary for SDS source mapping (**Figure 24**) includes:

- data on soil characteristics
- data on land cover
- data on soil condition

Here are separated soil characteristic and soil condition data, where:

- “characteristics” describes soil as a material (texture, composition, etc.), and
- “condition” describes the soil properties which change according to seasonal and weather conditions.

Both can be impacted by human activities (see **chapter 8.2 and 8.3**).

Data that can provide information about listed parameters are universally available, but quality may differ from region to region. To further increase the quality of SDS source maps, implementation of national data and information is necessary.

Soil characteristics

The most important information regarding soil characteristics is the soil texture and soil structure. Surface soil texture will provide information on soil particle size distribution, such as whether the soil contains particles that are small enough to be uplifted from the surface and carried away from the source (Lu and Shao 2001; Shao, 2008).

Such soil texture classes, based on the United States Department for Agriculture soil classification system,[1] are presented in **Figure 25**. Soil texture classes should include clay and silt size particles, but classes that have major part of sand size particles will not be ignored, just will be considered as less productive, because of their significant role in emission processes (Shao 2008; Sweeney et al., 2016). The most SDS productive soils, considering soil texture, are marked in red in **Figure 25**, medium productive in green and least productive in blue.

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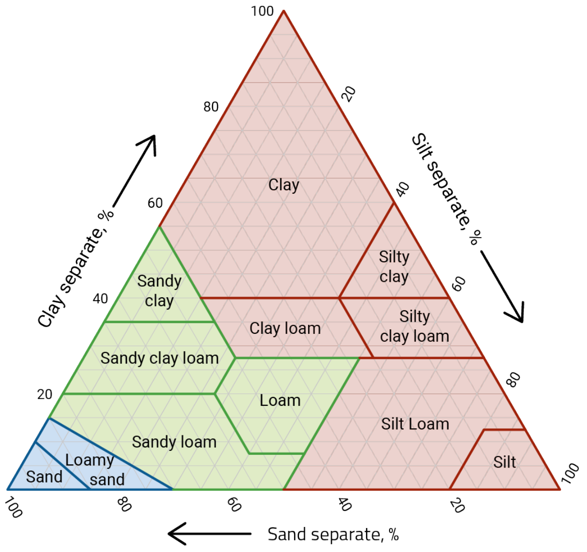
[1] See https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/.

Figure 25. United States Department of Agriculture soil texture classification system



Key: Red – soil texture classes with higher content of fine soil particles. Green – soil texture classes with medium to low fine soil particles content, Blue – dominant coarse soil texture.

Note: Adapted from Natural Resources Conservation Service (n.d.).

Information on the surface soil structure provides information on whether a soil surface is disturbed or loose. Aggregate stability is related to organic matter content (Chaney and Swift, 1984). Soil that has low structural stability is found to have very low content of soil organic carbon (SOC). Desert areas have values of about 0.2 per cent and other areas in arid climates about 0.5 per cent (Fan Yang et al., 2018).

Soil organic carbon is one of the indicators used to assess land degradation and monitor land degradation neutrality (Cowie et al., 2018). Degraded soils are vulnerable to wind erosion, a land degradation process linked to SDS source formation.

Usually, fine soil texture is related to richer SOC content (Meliyo et al., 2016; Johannes et al., 2017), but where there is a fine structure and low SOC, surface soil particles can be loose where other parameters show favourable conditions for the activation of SDS sources. Setting upper SOC thresholds can exclude surfaces that have good surface structure and where soil particles are in stable condition. Low values or decreasing SOC values can serve to identify areas with increasing exposure to wind erosion, and which can become SDS sources.

The depth to bedrock can be one more limiting parameter categorized under soil characteristics (Shangguan et al., 2016). If the soils are shallow, they are most likely not significant SDS sources. Other soil characteristics that are indicative of its mineral and biochemical composition are important for understanding the interaction of particles with the environment, and their impact on climate system and humans. However, such information is very scarce.

Only a few data sets on soil characteristics related to SDS generation are available on a global level (Nickovic et al., 2012; Journet, Balkanski and Harrison, 2014; Perlwitz, Pérez García-Pando and Miller, 2015), and the available information can be improved. Soil data in global data sets can be of low quality and not regularly updated. Improving soil data sets can be done using national-level data, which are, however, usually not publicly available.

Land cover

Land cover data can be used to identify surfaces that are bare or sparsely/partially vegetated, and without snow/ice cover or water bodies (Tegen et al., 2002; Kim et al., 2013; Vukovic et al., 2014).

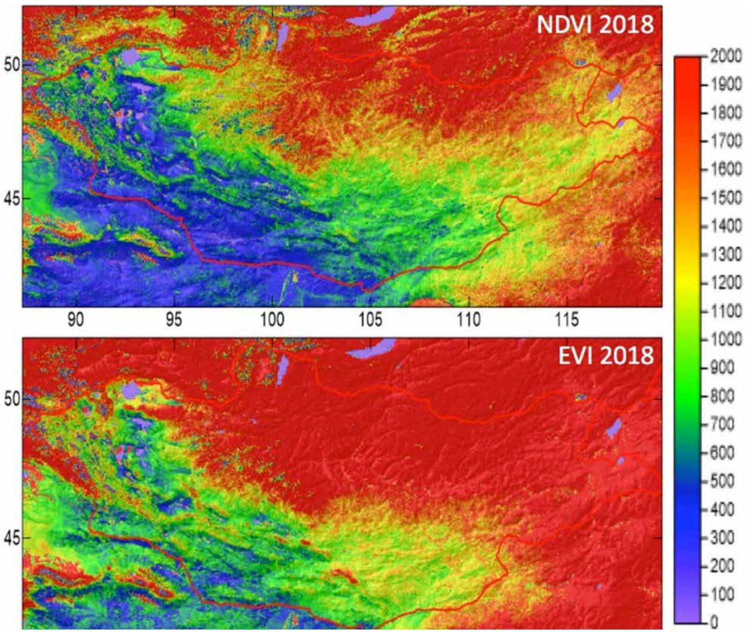
This information can be derived from regularly updated satellite data to detect changes in the activity of SDS sources. Parameters that can provide this kind of information are Normalized Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) data.

Land cover or land-use data are usually updated annually and can provide information about the type of surface (forest, grassland, cropland, bare, urban). Land cover types that can be considered potentially dust-productive are (i) bare land or (ii) sparsely vegetated land, grassland, scrubland and cropland. Other land cover types that can also be impacted by human impact drivers (see **chapter 8.3**.) can become anthropogenic sources due to the loss of ground cover, due, for example, to melting ice, fire or deforestation.

> Land cover data can be used to detect bare regions but are insufficient for detecting dynamic SDS sources. As a result, land cover data can be used together with NDVI/EVI data to detect types of SDS source.

A priority in SDS source mapping, related to land cover analysis, is to use NDVI or EVI data and land cover data in a more diagnostic manner to recognize types of the SDS sources. NDVI data are commonly used for SDS source mapping, but EVI can correct some distortions arising from atmospheric haze and ground cover below vegetation (Heute et al. 2002).

Figure 26 presents an example of NDVI and EVI data for 2018 for Mongolia where differences between these two indices are clearly visible. Red values represent areas covered with vegetation and blue values areas without vegetation. Updated SDS source maps at a national level based on NDVI/EVA data can be used to identify different types of the SDS source (pasture, mining, among others).



Note: Values are multiplied by 104.
Source: Personal communication, courtesy of Jungrack Kim

Figure 26. Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index (MODIS NDVI) and Enhanced Vegetation Index (EVI) for 2018

Soil condition

The most important parameters related to soil condition, which are mainly related to weather conditions but can also be impacted by human activities, are (i) soil moisture and (ii) soil temperature. These parameters are discussed as follows.

If topsoil with favourable soil characteristics is dry enough and not frozen, emission from the surface is possible in favourable windy conditions. If topsoil is drier, the wind velocity threshold for emission of particles is lower (Bagnold, 1941; Fécan, Marticorena and Bergametti; Nickovic et al., 2001; Pérez García-Pando et al., 2011). Soil temperature needs to be well below 0°C to be frozen, and the threshold may depend on soil composition (Kim et al., 2013). Soil freezing temperature also depends on moisture content, because low-moisture soils need lower temperatures to freeze, and in soil saturated with water, will most likely freeze at temperatures near 0°C.

Setting an upper threshold for moisture data and a lower threshold for temperature data will distinguish areas that can generate SDS if other parameters allow classification of these areas as SDS sources. More about data sources and data manipulation can be found in the next section.

Other data and improvements of sand and dust storm source mapping

Necessary data for SDS source mapping described in the previous section are available on a global level or can be derived from global data sets. At regional and national levels, further improvements of data quality and resolution are possible for most of the listed parameters, using regional and national data sets (**Figure 24**), such as soil types and composition, soil condition data, weather and climate data and information on human activities (Gerivani et al., 2011; Cao et al., 2015; Borrelli et al., 2016). Better diagnostics on SDS source types are also possible, especially of anthropogenic sources, for example, mining sites, conventional agricultural production sites, glacier retreat zones or loss of vegetation due to fires. Mapping of SDS sources at the national level, including spatial and temporal resolution improvements, can be done by implementing SDS source monitoring using remote sensing and high-resolution topographic and geomorphological information (Bullard et al., 2011; Parajuli and Zender, 2017; Feuerstein and Schepanski, 2019; Iwahashi et al., 2018). Improvements of SDS source mapping by implementation of topographic data are discussed in more detail in **chapter 8.6.4**.

8.6.2. Calculating the SDS sources spatial distribution

Calculations can be used to identify the likelihood of SDS source development based on a range of factors, including soil texture, soil structure, bare soil surface, soil moisture and frozen soil. Calculation processes described below focus on extracting and processing data to develop SDS source maps. The calculations detailed below are based on an assumption that land surface can be SDS-productive (land is SOURCE=1) and continues with filtering using values for the soil surface parameters explained as follows.

Soil texture

Data on soil texture provides the fraction (percentage) of clay and silt content. Higher clay and silt content mean higher potential for SDS formation. The United States Department of Agriculture (USDA) soil texture types that have fine particle contents sufficient for blowing dust and SDS formation, can have total clay and silt content mainly above 50 %. Surfaces with sand-dominant content should not be excluded but rather scaled as less productive than surfaces with higher content of clay and silt, because heavier particles less contribute to emission rates during high wind events and require higher wind velocities to carry them away from sources.

Setting up the lower threshold on total clay and silt content will exclude surfaces that are not significantly active because of the very high, coarse fraction content. Scaling soil texture potential for SDS formation is directly related to finer particle content:

SOURCE = FTX , if FTX < FTXmin then set FTX = 0

where FTX is a fine soil texture fraction with values 0 to 1. Threshold FTXmin is not necessary, as lower FTX values will reduce SOURCE function. However, adjusting threshold value may exclude surfaces that are insignificant, for example, for transport far from the source and long-range transport.

Soil structure

To distinguish soils with a loose surface, meaning that particles on the surface are more susceptible to wind erosion, values of SOC can be used. Arid and desert surfaces have low SOC content, well below 1 per cent (0.2–0.5 per cent), but for vulnerable areas that are experiencing soil degradation and can transform into SDS sources, SOC can be up to 1 per cent. SOC information is implemented in SDS source mapping by defining the upper threshold, and all soil surfaces with lower values can be considered to have unstable or low structure, and thereby susceptible to wind erosion:

SOURCE = FTX x STR, if $SOC < SOCmax$ then STR=1, if $SOC \geq SOCmax$ then STR = 0

where STR is the soil structure parameter and SOCmax is a defined threshold value, which depends on the interest in SDS source mapping, that is, only desert areas or areas that include surfaces vulnerable to wind erosion under extreme drought and negative human impacts. However, relations between wind erosion impact and SOC content is poorly known, and thresholds should be carefully chosen in order not to exclude potential dust emission areas.

Bare soil surface

The bare soil surface fraction in the grid box can be detected using NDVI (or EVI) values above zero to exclude water bodies, snow and ice cover. Values up to 0.1 fully distinguish bare surfaces, but areas with higher values can also include a fraction of bare soil surface.

The relation of NDVI values with a fraction of vegetation has not yet been determined, but according to the literature (which is mainly related to NDVI rather than EVI for this purpose), the upper boundary of 0.15 can include a major part of fully bare and sparsely vegetated surfaces. Water, snow and vegetation cover may change depending on the SDS source drivers. A regular update of the values of this parameter is recommended. Implementation of data on bare soil surface fraction (BSF) can be done as follows:

SOURCE= FTX x STR x BSF, if $NDVI > NDVImax$ and $NDVI \leq 0$ then BSF=0, if $0<NDVI\leq0.1$ BSF=1, and if $0.1 < NDVI \leq NDVImax$ then $1 \geq BSF \geq 0$ or also can be set to BSF=1 where BSF is the bare soil fraction with values from 0 to 1, depending on the NDVI (EVI) values, and NDVImax is the threshold for NDVI. This threshold value may be adjusted to different land cover types.

The relation of BSF and NDVI values, when the soil surface in the grid box is partially covered with vegetation, can be improved with the use of higher-resolution soil surface observations. Due to less noise in the EVI data compared to NDVI, the use of EVI should be considered.

Land cover or land-use data can be used to identify types of SDS sources, by overlaying this information with SOURCE data, and to double check exclusion of irrelevant surfaces. Land cover types that can be potential SDS source areas include bare land, grassland (pastures), cropland, scrubland (open scrubland). These data are updated annually.

Soil moisture

Soil moisture usually depends on the climate zone. However, as soil moisture varies seasonally and is dependent on weather conditions, a process of looking at soil moisture for all areas with possible low soil moisture permits the detection of seasonal and occasional SDS sources. This is particularly true at the beginning of the growing season.

Soil moisture measurements are usually very sparse and/or not available to the public. A few global data sets are available, from the European Centre for Medium-Range Weather Forecast (ECMWF) or National Oceanic and Atmospheric Administration (NOAA) analysis and satellite data. Data are updated every 6 to 12 hours, or daily. Relatively new ERA5-Land database provides data on higher spatial and temporal resolution, generated by surface scheme which is a part of the ECMWF forecast system, with available data at 1 hour interval.

If soil moisture (SM) is below a certain threshold, emission is possible:

SOURCE= FTX x STR x BSF x DSF, if $SM \leq SMmax$ than DSF = 1, if $SM > SMmax$ DSF = 0 where DSF is dryness of soil surface and permits SDS source activity if SM is below threshold SMmax.

Determining a threshold is not easy for two reasons:

1. Water capacity is different for different soil compositions.
2. Moisture thresholds where emission stops can change with wind velocity (higher value where there is higher wind velocity).

Adjusting SMmax can be done using information on drought, aridity, national data on soil types and their characteristics and values of SM that coincide with dry periods.

Frozen soil

Soil temperature (ST) is important for excluding frozen soil surface areas. This is especially important during winter and early spring seasons, when areas are without vegetation and strong winds are possible (usually in continental climates). Temperature thresholds for frozen soil are below -10°C in case of lower soil moisture and depend on soil composition. If the soil moisture is higher soil freezing temperature is increasing.

Temperature data can be derived as soil moisture data, from EMWF or NOAA reanalysis and satellite data, and are also updated in 6 to 12-hour cycles, or daily. It can be obtained from ERA5-Land database on higher spatial and temporal resolution. If soil temperature (surface air temperature can also be used) is above some threshold value, emission is possible:

SOURCE= FTX x STR x BSF x DSF x NFS ,
if $ST \geq STmin$ than NFS = 1, if $ST < STmin$
NFS = 0

where NFS is not a frozen soil surface and permits SDS source activity if ST is above threshold STmin. Issues related to determining this threshold are similar to those of SMmax but related to conditions favourable for soil freezing.

8.6.3. Data sources for sand and dust storm source calculations

The data sets described as follows can be used for SDS source mapping. The data sets are geo-referenced, in standard grid presentations and regularly distributed globally. However, a user should investigate possible sources of relevant data for their region which can improve SDS source mapping accuracy.

Soil texture (clay and silt content) and SOC data:

The International Soil Reference and Information Centre (ISRIC) world soil information database provides SoilGrids (soil global gridded information) which enables users to manipulate data online and to download data sets (Hengl et al., 2014; Hengl et al., 2017). Data sets are 1km resolution and higher, available in TIFF format and in WGS84 latitude-longitude projection. Another extensive source on soil data are FAO databases. The relevant links are:

- http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/
- http://www.isric.org
- https://soilgrids.org
- https://www.isric.org/explore/soilgrids
- https://files.isric.org/soilgrids/

Bare surface and land cover data:

NDVI and EVI data are Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua products. The global MOD13A3 data set is recommended, as it is updated every month and has been available since the year 2000, in 1km resolution in Sinusoidal projection. A more frequent 16-day product, available in higher resolution, is MOD13A2. The file format is HDF-EOS. The relevant links are:

- https://modis.gsfc.nasa.gov/about/
- https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD13A3/
- https://e4ftl01.cr.usgs.gov/

The recommended MODIS Land Cover Type product is MCD12Q1 Version 6 (variable LC-Type1 – IGBP classification scheme for land cover). It is updated annually and has been available since 2001 in 500m resolution in Sinusoidal projection. The file format is HDF-EOS. The relevant links are:

- https://lpdaac.usgs.gov/products/mcd12q1v006/
- https://e4ftl01.cr.usgs.gov/MOTA/MCD12Q1.006/

One tool that can be used for decoding the MODIS data and for data manipulation is R studio, with the following libraries: MODISTools, raster, gdal and gdalUtils." R studio may be commercial software (see https://www.rstudio.com/).

More information about NASA products and Earth data can be found here:

- https://earthdata.nasa.gov .

Another option for land cover data are provided by the European Space Agency Climate Change Initiative (ESA CCI) (Wei et al., 2018). Data sets are annual, available for the period 1992–2015, with a resolution of 300m. The file types are GeoTIFF and NetCDF. Registration is required to download data. The relevant links are:

- http://www.esa-landcover-cci.org
- http://maps.elie.ucl.ac.be/CCI/viewer/index.php

Soil moisture and temperature data:

For soil surface moisture and temperature data, it is recommended to use data sets from the European Centre for Medium-Range Weather Forecast ERA5 product, available for public use. Data are in 30km (0.25° x 0.25°) resolution, featuring hourly and monthly averages since 1979. Data projection is WGS84 latitude-longitude and the file format is GRIB. The decoding software is wgrib. Soil data are available for four depths. The relevant link is:

- https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

Another global reanalysis product is the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 Project, which provides data sets in much coarser resolution. Data is for the period from 1948, at 2.5°x2.5° resolution, with a 6-hour temporal resolution and daily averages (Kalnay et al. 1996). The file format is netCDF and the decoding software is NCL, Python and Fortran.

Soil moisture data is also available from the ESA CCI: ESA CCI SM version 04.2 ESA – CCI Surface Soil Moisture merged with the ACTIVE Product. Data sets are daily (reference time 00 UTC), in 0.25°x0.25° resolution, with two versions covering the period 1978 to 2016. The relevant link is:

- https://www.esa-soilmoisture-cci.org

Soil moisture and temperature data are available on higher spatial (0.1o) and temporal resolution (1h) in ERA5-Land database:

- https://www.ecmwf.int/en/era5-land

All data should be adjusted to the same projection, resolution and grid position for easy data manipulation.

8.6.4. Use of topographic data for sand and dust storm source mapping

Data on soil characteristics in global data sets are constantly improving. However, the quality of these data is likely inadequate for most parts of the world. This is due to the high spatial variability of soil composition, the limited areas sampled compared with the total Earth land surface and the lack of international data exchange. The most reliable parameter is soil texture. To further distinguish areas with finer particles from coarser topsoil, information on topography can be used.

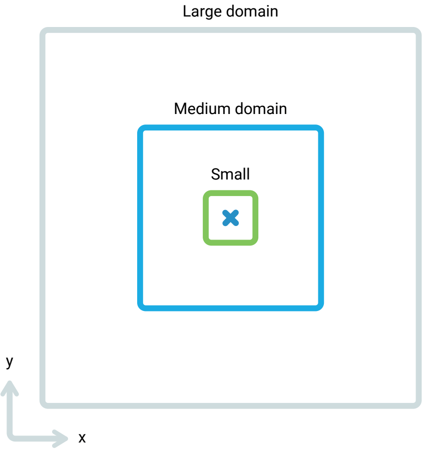
Under the assumption that alluvial deposits of fine soil particles are dominant in areas of dried river- and lake beds, and retreating glaciers, that is, in places exposed to increased erosion during the topsoil formation, SDS source mapping can be improved. Such areas are placed in topographical lows (pits), which can be derived from data on topography. Topographical lows can have large scales (such as the Taklamakan desert) due to very small areas – "hotspots" (for example, Iceland sources).

The simple approach described in Ginoux et al. (2001) and used for global dust forecast purposes in Kim et al. (2013) can be used to detect topographical lows. The function they used to estimate the fraction of alluvium available for wind erosion, at a point, scaled to values from 0 to 1 (lower values mean a low alluvium fraction is available, and higher values mean higher alluvium content), is now recognized as S-function. The S-function is calculated using maximum, minimum and in point altitudes, searching the values within the box 10°x10° around the point for which S is calculated. Simple modification of this approach is possible to include smaller-scale features (hotspots).

Figure 27 presents several domains for calculation of the value of the S-function in the middle (blue x). Applying this calculation in high-resolution and with different domains, large- and small-scale features of topographical lows can be recognized.

Figure 28 presents a vertical cross section of areas that S-function values recognize as topographical lows (pits), indicating the calculation of the S value for different domains (arrows). If high S values are recognized in all domains for the point (grid box) where the S-function is calculated, it is highly probable that the grid box is an SDS source hotspot, if allowed by other soil surface parameters. If values obtained for smaller domains have low values, it means that a large region is flat and most probably much less SDS-productive, but individual SDS source hotspots are possible.

Figure 27. Different size domains for calculation of S-function



Source: Ginoux et al., 2001.

Figure 28. Areas (arrows) indicate different domains identified as topographical lows

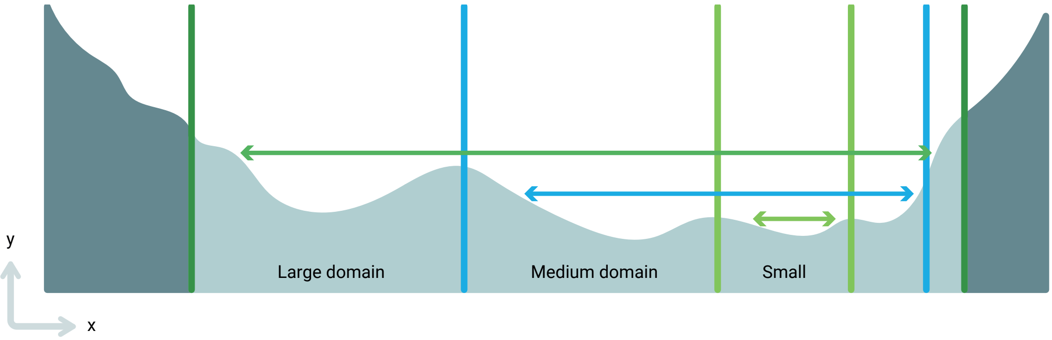


Figure 29 provides an example of a global calculation of the average S-function at 0.0083° resolution (30 arcsec, about 1km on the equator) using an ensemble of values obtained for four different size domains (10°x10°, 5°x5°, 2.5°x2.5°, 1.25°x1.25°). Values are obtained as the average of S-function results for different domains.

From the assumption based on S-function meaning, lower values contain a lower fraction of alluvium (which is considered SDS productive), and higher values most probably contain a higher content of SDS productive soils. Improving the identification of hotspots associated with alluvial deposits – which are of smaller spatial scale – is done by giving greater weight to results of S-function calculations using smaller domains or using higher-resolution topography data with a smaller domain for S-function calculation. To identify the most SDS-productive regions globally, identification of bigger pits is improved by giving greater weight to results of S-function calculations obtained with a larger domain. However, this results in a loss of fine high-resolution spatial source identification. The results of this process coincide with global SDS-productive regions (Ginoux et al., 2001). Note that **Figure 29** is an additional component for SDS source mapping and is not a map of SDS sources itself. S-function values are sensitive to i) the domain chosen for the calculation and ii) the resolution of topographic data.

Adding this kind of information to an SDS source map can help to distinguish more SDS-productive areas and exclude less significant areas:

PSOURCE = PSF x SOURCE

where PSF is preferential SDS-productive surface, with values 0 to 1. It can be derived using the approach provided by Ginoux et al. (2001) from an ensemble of S-function values derived for different domains. It is possible to obtain ensemble values that give more weight to the small-scale features, but that also provide information on larger impact areas, which may prove useful. Another way for using information obtained from S-function is to apply some adjustments (corrections) of soil texture data to enhance the content of fine soil particles content in areas where higher probability for higher alluvium content (higher S-function values).

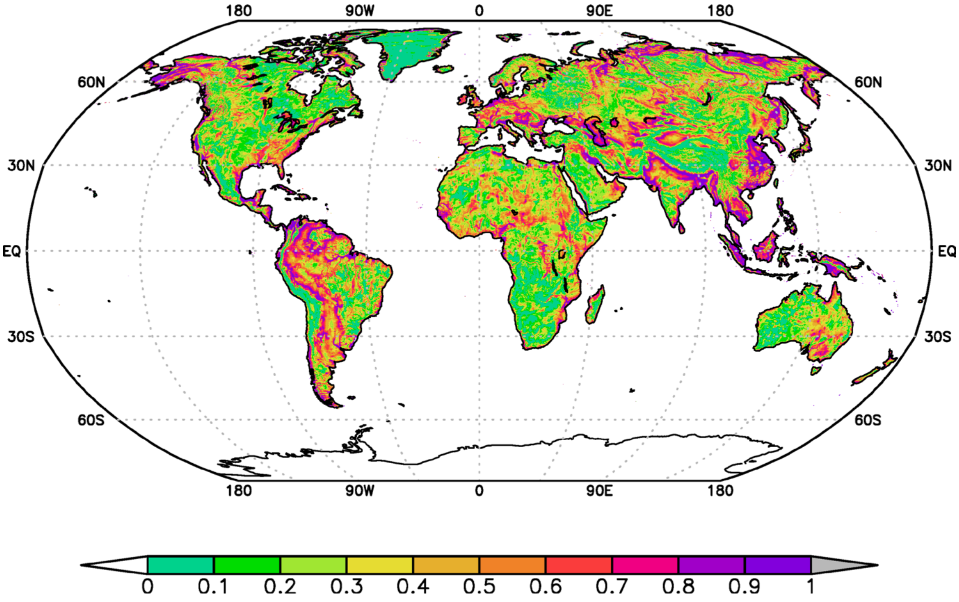


Figure 29. Average S-function values from four different domains (10°x10°, 5°x5°, 2.5°x2.5°, 1.25°x1.25°) on 0.0083° (30 arcsec) resolution, using topography data of the same resolution

Source: Ana Vukovic and Bojan Cvetkovic.

Besides using topographic data to distinguish more productive areas, other data sets may be employed (Zender et al., 2003). Geomorphology data sets may provide information regarding the location of alluvium (Bullard et al., 2011; Iwahashi et al., 2018), and PFS can be derived from such information.

Another example for implementation of topographic data in SDS source mapping is using watershed flow accumulation data (Feuerstein and Schepanski, 2019). If possible, monitoring and implementation of very high-resolution topographic data and local surface roughness using remote-sensing techniques may provide additional information for SDS source monitoring and higher-quality SDS source mapping (Menut et al., 2013; Yun et al., 2015; Demura et al., 2016; Kim 2017; Lin et al., 2018).

8.7. Conclusions

Choosing the methodology for SDS source mapping requires having a clear purpose for which the SDS source map will serve. If the purpose of the SDS source map is to estimate global distribution of major and most active global (or continental) SDS sources, without the need for a relatively precisely defined spatial pattern of most SDS-productive hotspots, mapping can be done using observations on SDS occurrence. This will serve to better understand aspects such as the global airborne dust cycle, regional dust transport and the seasonality of major sources.

If the purpose of SDS source mapping is to estimate the potential of soil surfaces to produce SDS in favourable weather conditions, a more complex cluster of data is required, as explained in the methodology for high-resolution SDS source mapping.

This approach enables a spatial SDS source pattern to be distinguished at high resolution, including most critical hotspots. This approach is recommended for vulnerability and risk assessments, especially for local SDS events, which are usually not very visible in SDS observations, as well as for planning SDS source mitigation and improving warning and alert systems.

Understanding the spatial and temporal variability of soil surface conditions and activity of SDS source areas depends on many factors. However, the use of national data sets and field observations can significantly increase the accuracy of SDS source mapping.

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