WEATHER CLIMATE WATER

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Sand and Dust Storm – Warning Advisory and Assessment System

Sand and dust storm (SDS) is a meteorological hazard, which is related to the process of wind erosion of surface soil and the mineral dust aerosol emission to the atmosphere. The frequent SDSs in Northern Africa, Middle East and Europe, Arabian Peninsula, Central Asia, northern India, northern, north-western China, southern Mongolia and adjacent Asian countries; and in desert regions of Australia and the USA seriously threaten human health, agriculture, aviation, ground transportation, solar energy industry, air quality, infrastructure and industry, as well as aquatic and terrestrial ecological systems. Dust aerosol can carry irritating spores, bacteria, viruses and persistent organic pollutants. It also transports nutrients to the oceans and affects marine biomass production, which affects the changes of greenhouse gases in the marine environment. The Inter-governmental Panel on Climate Change (IPCC) recognizes dust aerosol as a major component of atmospheric aerosol that is an essential climate variable. More and more, dust particles are considered by atmospheric researchers as an important factor influencing weather through feedback on atmospheric dynamics, clouds and precipitation formation. Understanding the processes that lead to SDS formation and evolution, obtaining the relevant parameters for SDS occurrence, development and change, providing the observational basis for describing the weather conditions associated with SDS, and carrying out numerical dust forecasts along with providing corresponding SDS early warnings are the urgent needs of effectively mitigating the impact of SDS and are also of great significance to the national decision-making in combating the impact of SDS.

The WMO Sand and Dust Storm Project was initiated in 2004 with the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) launched in 2007 with the mission to enhance the ability of countries to deliver timely and quality sand and duststorm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities (Nickovic et al., 2014, Terradellas et al., 2015).

Figure 1. SDS over Bikaner, Rajasthan, India on 2 May 2018

The SDS-WAS works as an international hub of research, operational centres and end users, organized through regional nodes (Figure 2). Three nodes are currently in operation:

- **Regional Node for Asia**, coordinated by a Regional Center in Beijing, China, hosted by the China Meteorological Administration.
- **Regional Node for Northern Africa, Middle East and Europe (NAMEE)**, coordinated by a Regional Center in Barcelona, Spain, hosted by the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Center (BSC).
- **Regional Node for Pan-America**, coordinated by a Regional Center in Bridgetown, Barbados, hosted by the Caribbean Institute for Meteorology and Hydrology.

Overview of the atmospheric dust content in 2018

The third Airborne Dust Bulletin reports on the global surface dust concentration in 2018, as well as the observational and forecast results of representative severe sand and duststorms around the world. The analysis presented in this Bulletin relies on a very limited

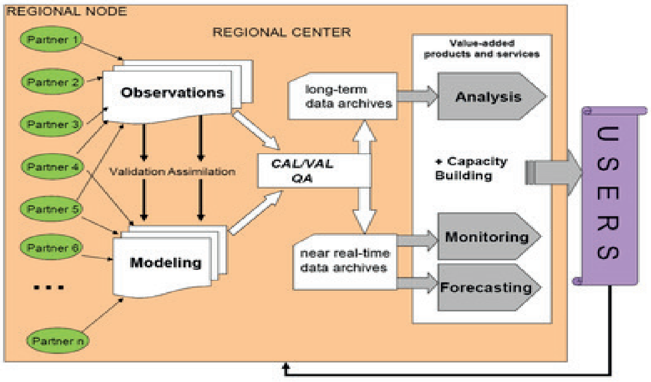


Figure 2. Schematic structure of current SDS-WAS Regional Node

observational database due to the paucity of suitable dust observations and the complexity of extracting specific dust signals from satellite radiances. In addition, observations from sensors working in visible channels are not available over bright surfaces such as deserts (Benedetti et al., 2014). To support limited observational evidence this report has been reinforced by the results of numerical models which incorporate observations through data assimilation, but uncertainties still persist.

The spatial distribution of global surface concentration of mineral dust in 2018 and its anomaly relative to the climatologically mean values (1981–2010) (Figure 3) are derived based on the dust products from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (Gelaro et al., 2017), which is the latest atmospheric reanalysis version for the modern satellite era produced by NASA's Global Modelling and Assimilation Office (GMAO). MERRA-2 includes an online implementation of the Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART) integrated into the Goddard Earth Observing System Model Version 5 (GEOS-5). MERRA-2 provides the capability for simulating five types of aerosols. The results shown here are based on the parameter of dust surface concentration, which is different from the parameter of dust aerosol optical depth (AOD), and more relevant to ground air quality.

In 2018, a well-known dust belt composed of major dust sources including northern and Central Africa, the Arabian Peninsula, northern India, Central Asia, the deserts in north-western and northern China can be clearly seen in the northern hemisphere (Figure 3). The estimated peak concentration of dust can be found in some areas of Chad in Central Africa (~900–1000 μg/m^3). High concentrations of dust can also be seen in some regions in the Arabian Peninsula, Central Asia, and north-western China with mass concentrations of ~400–600 μg/m^3. In addition, dust concentration can reach the highest level of ~200 μg/m^3 in the places of Central Australia in the southern hemisphere. From these sources, dust is transported to surrounding regions, such as the northern tropical Atlantic between West Africa and the Caribbean, South America, the Caribbean Basin, the Mediterranean, the Arabian Sea, and northern India or central-eastern China, Korea, Japan.

In the most dust plume affected areas, the surface dust concentration in 2018 is higher than climatological mean (Figure 4), except the areas in Central Africa including Mauritania, Mali, Niger, Nigeria and Chad, Central Asia, northern China and central-western Australia (Figure 4). Hot-spots with significantly higher dust concentration include northern Ethiopia and Yemen, north-eastern Saudi Arabia, Pakistan, northern India, and north-western China.

Several severe SDS events that occurred in these hot-spots in 2018 and which are presented below, resulted in deaths and serious social and economic losses.

Major SDS events over various regions in the world during 2018

SEVERE SDS EVENT IN INDIA IN MAY 2018

In India as per Hindu/another local solar/moon calendar (vary state wise), "Vaisakh/Vaisakha/Boishakh" season begins around mid-April that marks the beginning of the summer season. It is also known as notorious for SDSs that start as strong gusts from the north-western direction, causing widespread destruction. This period with frequent duststorms covering from April to June as per local calendar, is also known as "KalBaisakh" (or Nor'wester) and the storms are known as "Kal Baisakhi" (or Kalboishakhi) since ancient times where "Kal" refers to "Yam", the god of death brought by SDSs and thunderstorms. In 2018, surface dust concentration is found significantly higher than the long-term average (Figure 4) in Pakistan and northern India.

In Figure 5, a snapshot of the most devastating SDS event is presented. This event was one of the largest in the last three decades as per estimates of local residents. It struck north-western parts of India, including megacities like Jaipur, Delhi, Agra, Lucknow, on 2 and 3 May 2018. Most affected states, as per media reports, were Rajasthan, Delhi, Uttarakhand, Uttar Pradesh, and surrounding regions in the vast Indo-Gangetic (Ganga belt) plains. The death toll was reported to be around 35, 4, 73 in Rajasthan, Uttarakhand, Uttar Pradesh respectively and more than 400 people were injured.

The duststorm that struck India on Wednesday (2 May 2018) was associated with very high wind speed, extremely low visibility along with scattered thunderstorms and dangerous levels of PM_{10} and $PM_{2.5}$ leading to respiratory and allergy issues. High wind speed lead to injuries due to flying objects and zero visibility. Indian National

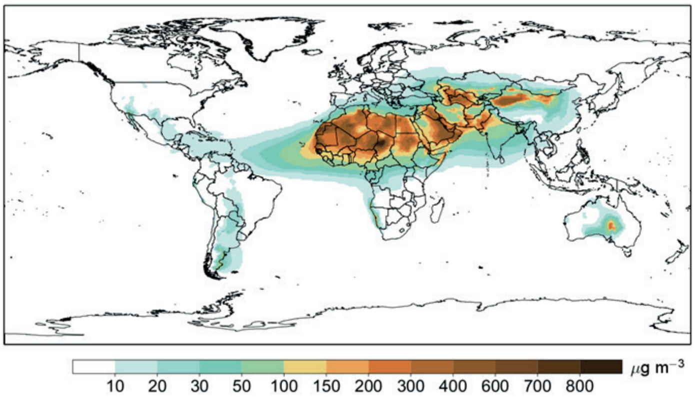


Figure 3. Annual mean surface concentration of mineral dust in 2018

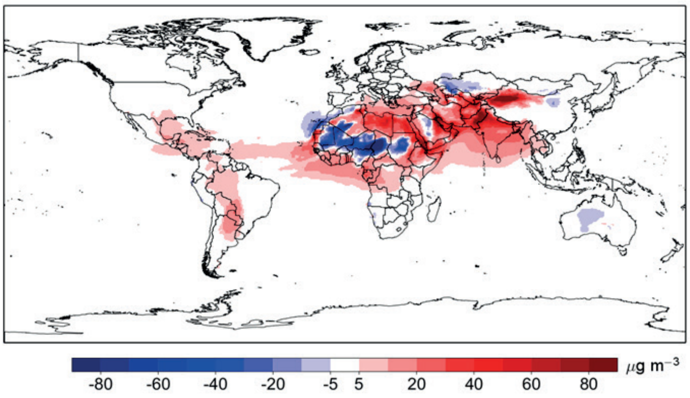


Figure 4. Anomaly of the annual mean surface concentration of dust in 2018 relative to mean of 1981–2010

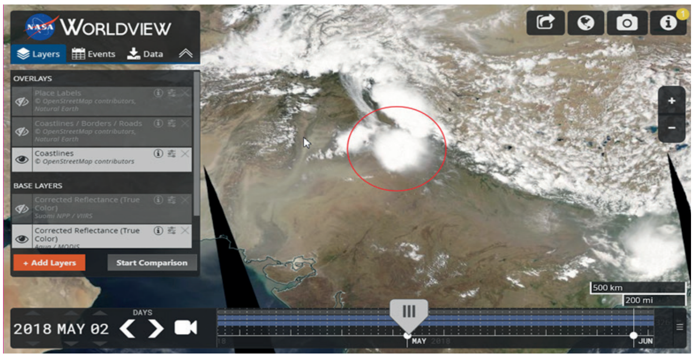


Figure 5. A high-speed SDS (Kal Baisakhi), marked as red circle, over the north-western part of India as visible in a near real-time satellite image taken on 2 May 2018 (downloaded from https://worldview.earthdata.nasa.gov). The image was taken by MODIS sensor onboard Aqua satellite and provided in near-real time by NASA.

Disaster Management Authority (NDMA) reported that Agra was one of the worst hit districts where at least 36 people died. Media reported deaths of approximately 43 people in a village near Agra alone. Over 150 animals also died during the duststorm. Down-to-Earth (https://www.downtoearth.org.in) reported total casualty to be over 400 people across 16 states during the 2018 duststorm season. The Asian Node Center provided a numerical forecast of this severe SDS event in India on 2 May 2018 (Figure 6). Improving forecasts of very small-scale SDS events is still an emerging research issue facing the world.

This severe SDS event resulted in widespread uprooting of hundreds of trees and electricity poles, trees falling on houses and high-speed winds resulted in collapse of mud walls of houses or roofs, and even AC fittings in urban areas leading to no electricity and acute shortage of water supply during the period. In anticipation of an increase in the numbers of people killed or injured in the duststorm, state governments also issued alerts for the next 48 hours and started rescue and relief works to save people buried under the debris and restore power supply.

SDS EVENT IN WESTERN ASIA IN FEBRUARY 2018

From a global SDS perspective, West Asia has been widely recognized as one of the regions heavily affected by SDS. This can be seen from the estimated surface dust concentration in Figures 3 and 4. Khuzestan can be considered as one of the hotspots in this area. Khuzestan is an Iranian province located at the southwest of the country, bordering Iraq and the Persian Gulf. Duststorms have become a major environmental concern during the last decades in this oil- and gas-rich province. Zarasvandi et al. (2011) estimated an average occurrence of 47 duststorm days per year with this figure increasing at a rate of two days per year. They also pointed out that the major dust sources affecting Khuzestan are dry lakebeds, alluvial deposits and deserts in neighbouring countries to the west. In particular, the Mesopotamian marshes are suffering rapid land degradation, caused by natural and human-induced factors, and might vanish soon in the future, thus expanding the source area (Cao et al., 2015). On the other hand, local dust sources are also important. They are associated with a desert climate and poor, often salty, river flows that leave bare soils exposed to erosion.

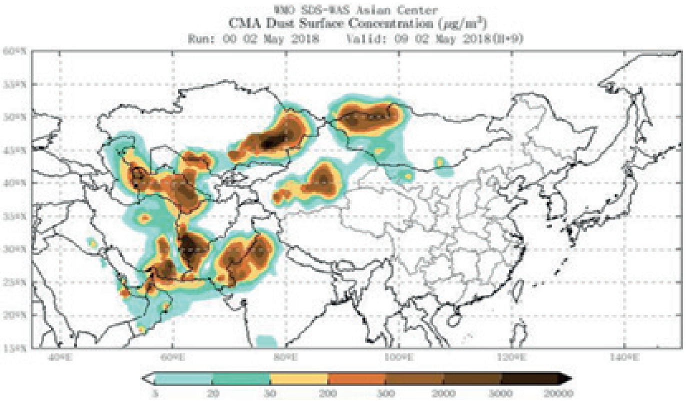


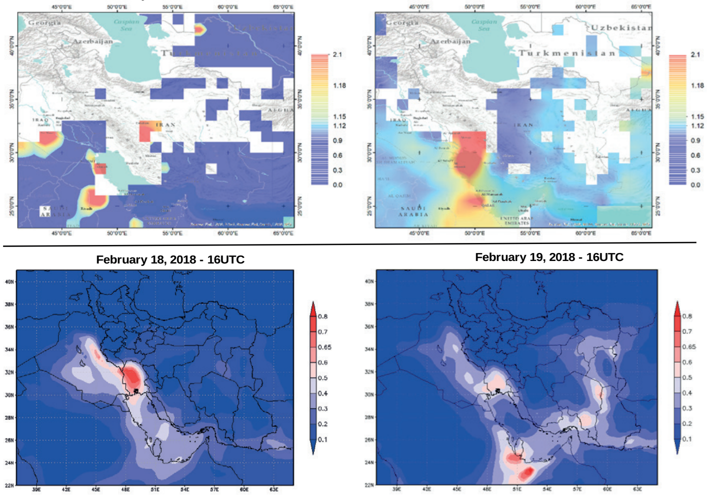
Figure 6. The surface dust concentration output by the CMA_CUACE/Dust model for 09UTC on 2 May 2018 (http://eng.nmc.cn/sds_was.asian_rc)

An SDS episode which occurred in February 2018 is described to illustrate the severity of SDSs in Khuzestan. On the morning of Sunday 18 February 2018, the frontal type dust was activated in Kuwait and Iraq which affected Khuzestan. The concentration of dust in the cities of Abadan and Khorramshahr was about 66 times higher than the permitted limit, and the horizontal visibility in these cities decreased to about 100 m which resulted in the cancellation of two flights from the International Airport of Abadan. The schools of the Mahshahr, Shadegan, Abadan and Khorramshahr cities were closed due to the occurrence of dust phenomena in the afternoon. In addition, the wind speed measured ~50 km h^{-1} during the storm in the morning of 18 February 2018, caused suspension of local dust in some parts of the province, including Ahvaz, Abadan, Omidieh and Izeh, while horizontal visibility in Ahwaz reduced to 500 m (Islamic Republic News Agency). On 19 February 2018, the measured dust concentration within this dust event was higher than 983 ug/m^3, which lead to the closure of all schools in 11 cities of this province (ISNA News Agency).

The aerosol optical depth (AOD) product of the MODIS generated by the combination of dark target and deep blue algorithms and the dust model output are shown in Figure 7. Due to the dense cloud cover in large parts of the region, AOD is not retrieved homogenously, though high AOD is seen in Kuwait, North-eastern Saudi Arabia, Persian Gulf and Khuzestan province in southwestern Iran. The AOD output of the BSC_DREAM8b_V2 model from the NAMEE node of SDS-WAS (https://sds-was.aemet.es) is also shown in Figure 7. The results show that the pattern produced by the model is in good agreement with the MODIS AOD products.

SEVERE DUST EVENT IN PHOENIX, ARIZONA, USA IN AUGUST 2018

Central Arizona is located in the desert southwest region of the United States of America and is a region prone to blowing dust events. These events are common during the North American “monsoon season” which mainly spans from July to August and is characterized by thunderstorms occurring almost daily. SDS events are usually formed by the outflow from thunderstorms and can travel long distances wreaking havoc with increased visibility which



February 18, 2018 - 16UTC

February 19, 2018 - 16UTC

Figure 7. The aerosol optical depth (AOD) product of MODIS generated by the combination of dark target and deep blue algorithms for 18-19 February 2018 (upper panel). The AOD output of the BSC_DREAM8b_V2 model from https://sds-was.aemet.es/ for 18-19 February 2018 (lower panel).

can lead to vehicle accidents. Major sources for duststorms in central Arizona are the mountainous areas of north-central Mexico in Sonora, the mountainous regions of the Mogollon Rim in Arizona, and the Gulf of California. Locally, land use practices, wind patterns and ground moisture control dust loading in specific areas.

A report published by the National Weather Service (NWS) in 2016 states that “based on statistics from 1955 through 2013, blowing dust is ranked as the 3rd deadliest weather phenomenon in Arizona after flooding and extreme heat and cold”. Additionally, according to (Tong et al., 2017), the frequency of duststorms is found to be correlated with Valley fever incidences.

On Thursday 2 August, what started as a typical warm and humid summer day across Arizona turned out to be more exciting than what was anticipated. According to the preliminary storm report from the NWS Phoenix, what was a little more unusual was a weak weather feature moving west-to-east through the Mountain West, the far southern tail of it dragging across Arizona. In addition, other weak features across northern Mexico slowly moving east-to-west were present. This resulted in showers and thunderstorms developing during the afternoon hours, over western and northern Arizona and then across southern Arizona. The storms to the south developed into a cluster of strong storms and moved northward into central Arizona.

The strong thunderstorm outflow winds caused a large duststorm to develop and move south-to-north across Maricopa and Pinal counties. The NWS Phoenix warned that the duststorm was approaching (Figure 8). The duststorm was expected to cause “near zero visibility with damaging winds in excess of 60 mph” and could also cause “dangerous life-threatening travel.” Drivers were warned of impaired visibility across the county and instructed to avoid being on the road or, if caught in the storm, to pull off to the side of the road.

There were several reports of near zero visibility early in the storm, though the intensity of the duststorm weakened as it moved northward into the Phoenix area. This weakening was attributed to a lack of new dust to ingest and decreased intensity of the thunderstorm outflow. The duststorm caused significant disruptions in several activities in the city including knocking out power at Chase Field and disrupting play at Goodyear Ballpark.

SDS PROCESS IN HIGH LATITUDES OF THE NORTHERN HEMISPHERE

WMO Airborne Dust Bulletin No. 2 reported on the high-latitude dust (HLD) which is a mineral aerosol with potentially important environment and climate impacts. Icelandic deserts, being the largest European source of mineral dust in the Arctic region, is of particular interest to general public and researchers. Emitted dust particles under strong wind conditions are mainly of volcanic origin. Under favourable conditions, Icelandic dust can be transported downwind up to a thousand km (Arnalds et al., 2016). More than a quarter of a year, there are dusty days in Iceland during which air quality is often substantially reduced thus potentially affecting human health. Road traffic is also affected due to reduced visibility under such conditions (Figure 9). Several car accidents are reported due to duststorms in South Iceland every year. This dust, having several times more iron oxides than for example Saharan dust, is likely an important primary nutrient of the high-latitude marine environment. Finally, this kind of dust plays a role in the Earth climate system: when deposited over terrestrial surfaces, it changes the albedo of snow and glacial areas, it also reduces the acidity of the high-latitude ocean where acidity has increased over last decades due to climate change.

Several recent modelling studies have been performed to simulate transport of Icelandic dust and its effects (Groot Zwaaftink et al., 2017; Beckett et al., 2017), but none of those models had operational capabilities and appropriate dust treatment.

The Republic Hydrometeorological Service of Serbia, in collaboration with the Agricultural University of Iceland (AUI), has applied a version of the Dust Regional Atmospheric Model (DREAM) (Nickovic et al., 2014), modified to function over the corresponding geographical domain. In this collaboration, AUI has provided detailed data on dust sources in Iceland. The AUI Soil Erosion

Figure 8. Duststorm moving into Phoenix, Arizona on 2 August 2018 (Source: Jason Ferguson)

Figure 9. Reduced visibility and air quality in Iceland during an SDS event.

Database and a survey of dust hot-spots is described in Arnalds et al., 2016. For the first time, operational prediction of dust dispersion in high latitudes was made available, see Figure 10 (http://www.seevccc.rs/?p=8; select Dream8iceland). The new forecasting system thus achieves the objective of SDS-WAS to deliver timely and quality SDS forecasts to users for this particular region.

Tourists in Iceland exceed more than six times the number of local inhabitants. As one of the top cycle tourism destinations Icelandic authorities need to raise awareness of duststorm danger (Figure 9). Dust forecasts are crucial for road safety in South and Northeast Iceland.

SDS EVENT OVER EASTERN ASIA in MARCH 2018

The influence of SDS on East Asia, originating from the deserts of north-western, northern China and southern of Mongolia peaks during the spring months. When a severe SDS event occurred from 27 to 29 March 2018, two geostationary meteorological satellites in the East Asian region caught its occurrence and development (Figures 11 and 12). The dust was emitted firstly from the desert regions of Mongolia, and then the dust plumes were observed in north-eastern China associated with the eastward moving of the Mongolian cyclone (Figure 11). The visibility decreased to less than 1 km in the heavy dust area within Inner Mongolia. This SDS event influenced several provinces of China, including Xinjiang, Inner Mongolia, Shanxi, Hebei, Beijing, Tianjin, Liaoning, Jilin, and Heilongjiang, affecting the area about 1.5 million square kilometres.

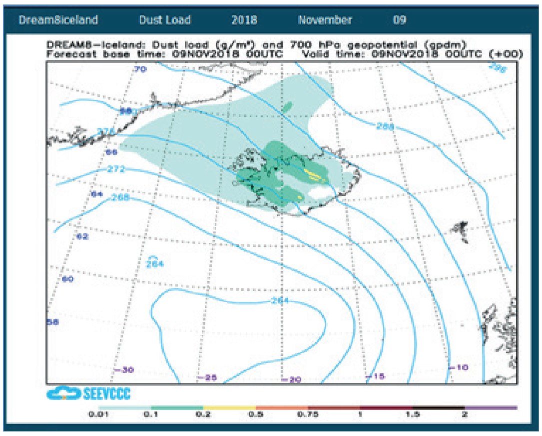


Figure 10. Example of the operational Icelandic dust forecast

The SDS-IDDI (Infrared Difference Dust Index) data are obtained from operational automatic identification and real-time retrieving system for the dust aerosols through combining the separating-window and spectrum gathering methods from the Asian Node Center of WMO SDS-WAS, derived by the National Satellite Meteorological Center (NSMC) of Chinese Meteorological Administration (CMA). The updated IDDI data are based on FY4A satellite retrievals that are used in the Data Assimilation System (DAS) associated with CUACE/Dust model utilized in this Center. The retrieval methodology and reliability of IDDI was first tested using Chinese FY-2C remote sensing data described in Hu et al., 2008; the DAS utilization was first reported by Niu et al., 2008.

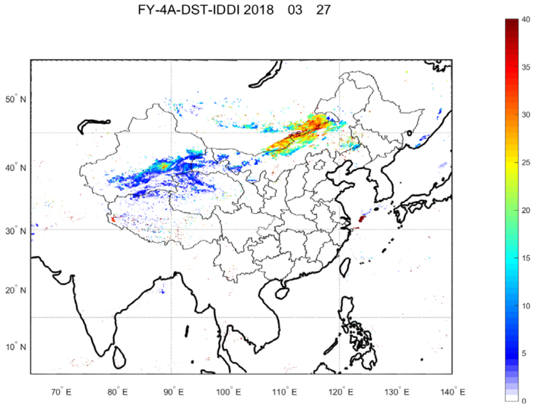


Figure 11. The SDS-IDDI (Infrared Difference Dust Index) retrieved from the China FY4A satellite for the SDS event on 27 March 2018

With the development of this SDS event, dust plumes were also observed in some areas of the Korean Peninsula and Japan. The Dust RGB image from the Himawari-8 satellite for 12 UTC on 27 March 2018 also shows that dust was swept up over north-eastern China. Figure 12 shows the True Colour Reproduction (TCR) image from Himawari-8 for 00 UTC on 29 March 2018. Korea Meteorological Administration and the Japan Meteorological Agency have been providing SDS event observation and forecast information in the SDS-WAS Asian Node, for supporting measures against damage due to SDS.

This severe SDS event was well forecasted by the models of the Asian Node Center. The dust surface concentration from the ensemble models in the Asian Node Center from http://eng.nmc.cn/sds_was.asian_rc is shown in

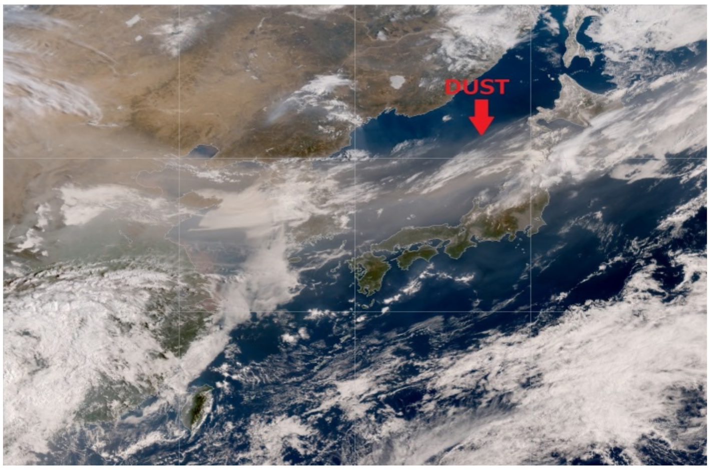


Figure 12. True Colour Reproduction image from the Himawari-8 satellite for 00 UTC on 29 March 2018

Figure 13. The results show that the pattern reproduced by the models is in good agreement with the ground-based observation of SDS events.

Capacity building

WARNING ADVISORY SYSTEM FOR SAND AND DUST STORM IN BURKINA FASO

Burkina Faso is a land-locked African country lying in the transition zone between the Sahara to the north and the humid equatorial region to the south. It has a primarily tropical climate with a rainy season from May/June through September, a little shorter in the northern part of the country, and a dry season, when a hot dry wind called harmattan blows from the Sahara. During the dry season, frequent duststorms are one of the main meteorological hazards affecting the population. Outbreaks of meningococcal meningitis, a bacterial infection of the thin tissue layer that surrounds the brain and spinal cord, occur worldwide, yet the highest incidence is found in the "meningitis belt", a part of sub-Saharan Africa extending from Senegal to Ethiopia and including the entire territory of Burkina Faso.

A warning advisory system for sand and duststorms has been launched for the 13 administrative regions into which the territory of Burkina Faso is divided: https://sds-was.aemet.es/forecast-products/burkina-faso-warning-advisory-system. Its core is a universally understood product based on colour-coded maps that indicate the risk of high dust concentrations during the next 48 hours (Figure 14). The warning levels are computed using the dust surface concentration predicted by the SDS-WAS multi-model median, which is daily generated from twelve numerical predictions released by different meteorological services and research centers around the world. The warning thresholds are set differently for each region as they are based on the climatology of the prediction product itself, using a percentile-based approach.

This system has been designed and is operated by the State Me-teorological Agency of Spain (AEMET) and the Barcelona Su-percomputing Center (BSC) in collaboration with the Burkina Faso National Meteorological Agency.

CHALLENGES IN DUST OBSERVATION IN REMOTE DESERT REGIONS

Measuring atmospheric dust near the sources is not a trivial issue. Most of the desert regions where mineral dust is lifted and transported over long distances are very sparsely populated and poorly communicated remote regions in which the deployment, maintenance, and periodic calibration of instruments are complex tasks due to logistical limitations. Under the WMO SDS-WAS NAMEE Node Regional Center, and through the WMO CIMO Izaña Testbed for Aerosols and Water Vapour Remote Sensing instruments, some projects are currently being developed to improve dust observation capacity in these regions, and specifically, in the Sahara desert. The most important parameter to characterize and monitor atmospheric dust variations is AOD, together with the derived Ångström Exponent parameter, with which dust predominance over total aerosols can be assessed. AOD is also commonly used to evaluate dust observations from satellite and modelled dust concentrations. Two different approaches have been followed. Firstly, a new methodology based on the comparison of down-welling zenith sky radiance observations performed with a zenith-looking multichannel radiometer with a look-up table of computed zenith sky radiances is used to estimate AOD. This technique provided excellent results compared to those from classic sun-photometers (Almansa et al., 2017). It avoids the use of suntracking, making it more robust, automated, and available at a lower cost. Secondly, within the frame of the Global Learning and Observations to Benefit the Environment (GLOBE) Program, the capacity of low-cost handheld photometers for dust-event observations and early warning is being tested. Although these photometers were discarded decades ago by WMO for aerosol monitoring under background conditions due to their poor accuracy and low long-term stability, their enormous utility for dust-event detection in desert areas has been demonstrated (Guirado et al., 2014). Currently, the possibility of using very low-cost handheld photometers to report quantitative column dust information every 3 hours as part of SYNOP reports from many small aerodromes located in remote regions is a plausible option suitable for model data assimilation and AOD satellite data evaluation.

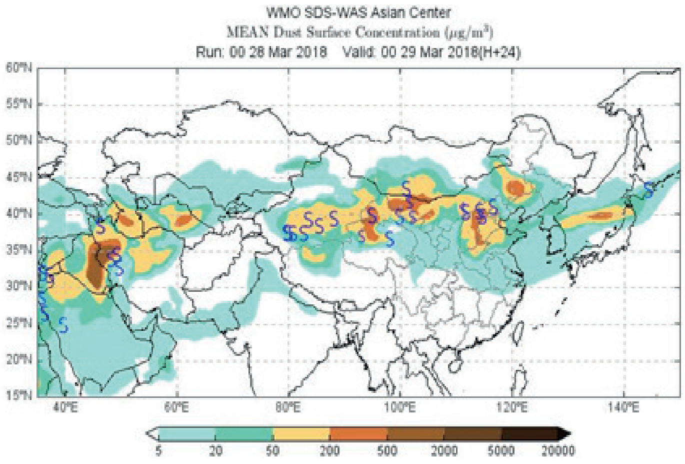


Figure 13. Ensemble mean surface dust concentration from Asian Node Center and observed SDS events at 00 UTC on 29 March 2018

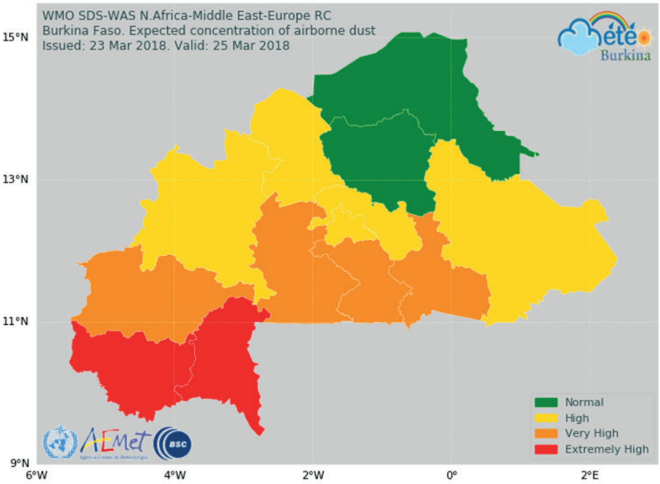


Figure 14. Warning advisory product released on 23 March 2018 valid for 25 March 2018

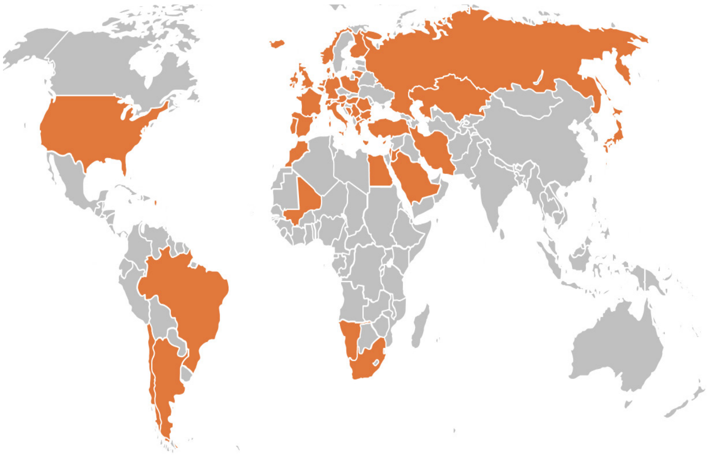


Figure 15. inDust participating countries. At present, the network includes 48 countries coloured in orange on the map.

inDust – LOOKING FOR DUST SERVICES

As a complement to the research mission of the WMO SDS-WAS, the international consortium of the EU-COST Action "International Network to Encourage the Use of Monitoring and Forecasting dust Products" (inDust, www.cost-indust.eu) has been launched in 2017 to make better exploitation of dust information on the end user side. inDust is searching to identify the gaps in the dust research as well as to exploit dust observations and forecast products best suited to be transferred/tailored to the needs of end users. Within these objectives, inDust is building capacity through the high-level training of end users (stakeholders from different socio-economic sectors) to use delivered dust products efficiently, and to establish collaboration between project partners in the inDust network through the organization, participation and support of different events such as training schools, conferences and workshops.

Because, airborne dust transport has diverse effects at local, regional and global scales, inDust network involves a multidisciplinary and international group of experts on aerosol measurements, regional aerosol modelling, stakeholders and social scientists as well as potential end users from different socio-economic sectors affected by the presence of high concentrations of airborne mineral dust (e.g. health, energy and transportation) from 48 countries (see Figure 15).

THE IMPACT OF DUST ON THE GENERATION OF SOLAR ENERGY

Dust plays an important role in solar technologies, especially in Concentrating Solar Power (CSP). Its influence on optical losses at mirror surfaces, the incoming radiation profile as well as on the atmospheric extinction is of importance to project developers, plant owners and operators.

The dust deposition (soiling) of Photovoltaic (PV) panels or solar mirrors of CSP plants reduces the output of the power plant and increases the cleaning costs as well as water consumption which is especially an issue in desert environments (see Figure 16).

The cleaning operators have to find the best trade-off between reduced cleaning costs and increased optical solar plant efficiency. A parameter to describe the effect of soiling is the cleanliness of the mirror/PV module. The cleanliness is calculated by comparing the reflectivity/short circuit current of a soiled mirror/panel to its reflectivity/ short circuit current in the clean state. The site and time-dependent soiling-rate is defined as the daily loss of cleanliness. CSP soiling rates are approx. 8–10 times higher than PV (for example, 0.35%/day and 0.04%/day at the Plataforma Solar de Almería, Spain) (Bellmann, 2017). Measuring, modelling and forecasting of soiling therefore helps to increase the plant output as well as decrease water consumption by optimizing cleaning strategies. Methods to measure and model site-dependent real-time soiling rates and methods for mitigation have been developed and validated (Wolfertstetter et al., 2012, 2018). In a recently started European project, the integration of a soiling model to the NMMB-MONARCH atmospheric dust forecasting model run at the Barcelona Supercomputer center is foreseen. The aim of the activity is a 72 hour forecast of soiling rates as well as a soiling map that can be used in CSP plant site selection.

Airborne dust particles also affect the contribution of circumsolar radiation to direct normal irradiance. Depending on the atmospheric conditions, a considerable fraction of solar radiation is scattered towards the circumsolar region (Figure 17). Circumsolar radiation is only partially used by concentrating collectors and therefore sunshape measurements have to be considered for performance evaluation of CSP plants. Not considering the correct contribution of circumsolar radiation in plant yield simulations lead to under- or overestimations in the annual yield of several percent (Wilbert et al., 2018).

The site- and time-dependent loss of radiation between the heliostat field and the receiver of a CSP tower plant due to atmospheric extinction also significantly influences its efficiency (Figure 18).The absorption and scattering processes in the atmosphere can cause higher losses than accounted for in standard plant optimization tools (for example, several percent of the annual plant yield in desert regions). Different measurement methods and models suitable for CSP resource assessment have been developed recently to enable a site- and time-dependent atmospheric attenuation evaluation and therefore to optimize CSP plants design (Hanrieder et al., 2017).

Figure 16. Soiled PV panel (left) and CSP trough (right)

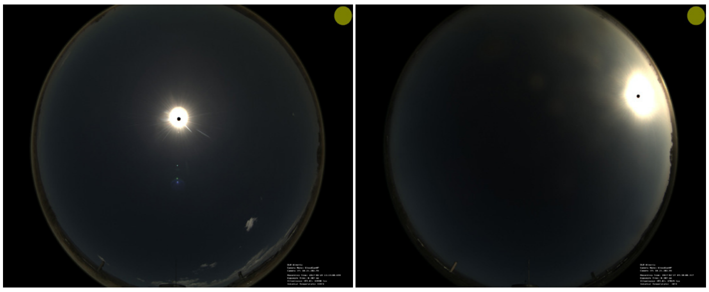


Figure 17. Circumsolar radiation is forward scattered solar radiation. Concentrating collectors use nearly the complete disk radiation and a smaller fraction of the circumsolar radiation.

Figure 18. CSP tower plant CESA1 at the Plataforma Solar de Almería on a clear (left) and hazy (right) day.

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