WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION | GLOBAL ATMOSPHERE WATCH | WWRP WORLD WEATHER RESEARCH PROGRAMME

WMO AIRBORNE DUST BULLETIN

No. 2 | May 2018

ISSN 2520-2928

Sand and Dust Storms (SDS) create multiple environmental risks in arid and semi-arid regions of the planet. They occur when strong or very turbulent winds blow over dry, unvegetated soils and lift loose particles from the Earth's surface to the atmosphere. The main factors that drive variations in SDS frequency are the drastic changes in annual rainfall and temperature and unsustainable land management and water use.

Over the last decades, the social interest in and the eagerness of the research community to enhance the understanding of the physical processes associated with the dust cycle, to predict future events and to prevent their undesired impacts has increased rapidly. Two resolutions from the United Nations Global Assembly (A/RES/71/219 in 2015 and A/RES/70/195 in 2016) have recognized the importance of the SDS problem and called on United Nations entities to promote a coordinated approach to combat SDS globally.

The **World Meteorological Organization** (WMO) was one of the first United Nations Agencies, which started addressing the problem of SDS, their observation, assessment and forecasting in response to the request of 40 member countries. In 2007, the 15th World Meteorological Congress highlighted the importance of the SDS problem and launched the **Sand and Dust Storm – Warning Advisory and Assessment System** (SDS-WAS). More than 15 organizations currently provide daily global or regional dust forecasts in different geographic regions. The WMO SDS-WAS, which is a global federation of partners organized around regional nodes, integrates research and user communities (e.g. health, aeronautical, and agricultural users). Presently there are three Regional Nodes: the Northern Africa-Middle East-Europe Node (with its Center hosted by Spain), the Asian Node (with its Center hosted by China) and the Pan-American Node (with its Center hosted by Barbados) that are coordinated by the SDS-WAS Steering Committee. In February 2014, WMO designated the Barcelona Dust Forecast Center as the first centre to operationally generate and distribute dust forecasts for Northern Africa, Middle East and Europe. In May 2017, WMO approved the second operational centre, with Asia as its geographic domain, hosted by China.

Overview of the atmospheric dust content in 2017

This second **Airborne Dust Bulletin** reports on the atmospheric burden of mineral dust through 2017, its geographical distribution and inter-annual variations. The report has been compiled based on the **Modern-Era Retrospective analysis for Research and Applications, Version 2** (MERRA-2), which is the latest atmospheric reanalysis of 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** Version 5 (GEOS-5) modelling system. GOCART simulates mineral dust together with other aerosol species: organic carbon, black carbon, sea salt and sulfate aerosols as well as sulfate aerosol precursors (Gelaro et al., 2017). MERRA-2 also includes assimilation of Aerosol Optical Depth (AOD) retrieved from satellite radiometers (AVHRR, MODIS and MISR) as well as from the Aerosol Robotic Network of ground-based sun-photometers (AERONET) (Randles et al., 2017). It is noteworthy to highlight that the results shown here are consistent with those obtained by the **Copernicus Atmosphere Monitoring Service** (CAMS), whose data were used in last year's report.

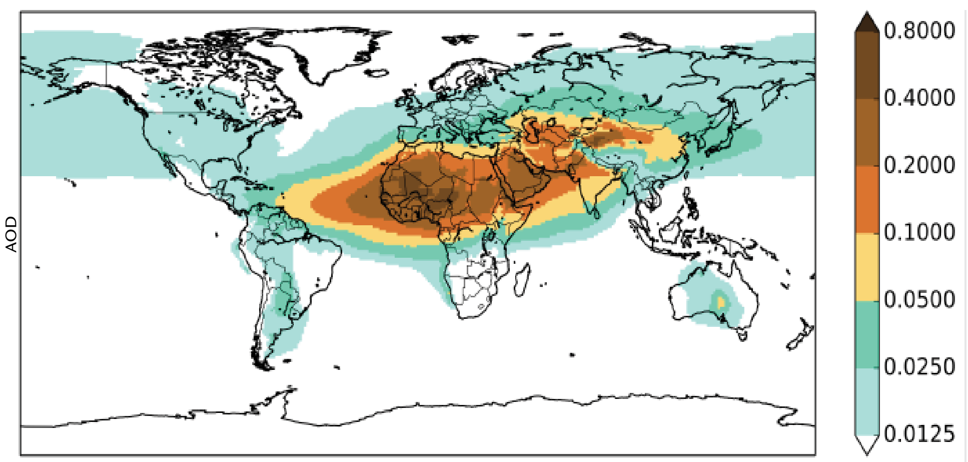

Figure 1. Annual mean distribution of dust AOD in 2017

The spatial distribution of the yearly-averaged airborne dust content in 2017 (Figure 1) follows a pattern similar to that of 2016 (Airborne Dust Bulletin, No. 1) and also to that of the climatic values found in the literature (i.e. Ginoux et al., 2001). The parameter represented in the plot is dust AOD, a measure of how dust particles block sunlight by absorbing or by scattering light. Most of the dust is concentrated around its main sources – the belt of tropical and subtropical deserts of the northern hemisphere as well as the mid-latitude deserts of Central Asia and China-Mongolia.

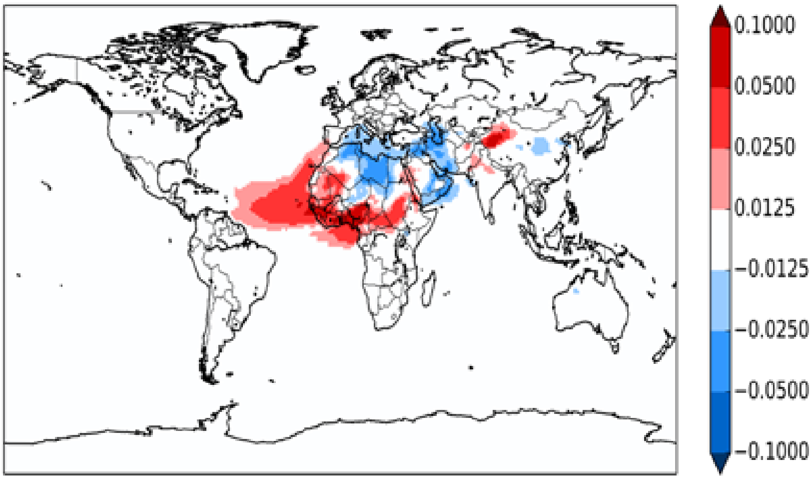

Figure 2. Anomaly of the annual mean distribution of dust AOD in 2017 compared to reference values 2003–2016

From these sources, dust is transported to surrounding regions. The strip of the northern tropical Atlantic stretching between West Africa and the Caribbean turns out to be the main transport route at a global scale. A significant part of the dust particles raised in the Sahara is transported along this path until they are deposited on the ocean, on the Caribbean or in Central and South America. An episode of dust transport to America occurred in early April is described in the next section. AOD reached values of 0.6–0.7 in the Eastern and South-eastern Caribbean and air quality was notably impaired by dust transported from the Sahara.

In the Northern Africa region, comparison of the 2017 dust AOD average with the 2003–2016 reference levels (Figure 2) suggests that the dust sources of the western part, especially those in Southern Algeria, Mali and Mauritania, have been more active than usual, whereas emission has been relatively low from the Libyan desert. Then, transport has been directed mostly towards the Americas and the Gulf of Guinea, while dust outbreaks in the Mediterranean and Southern Europe have been less frequent than in previous years. As an exception, we can mention an episode in mid-October, when the strong southern flow associated with the Ophelia cyclone carried considerable amounts of Saharan dust to the north affecting Western Europe and specifically the British Isles, where deterioration in air quality was aggravated by the huge amount of soot transported from the fierce forest fires in Portugal and Spain.

The presence of dust has been a little lower than average throughout West Asia, with the exception of the areas near the Red Sea. However, there have been some significant dust events. As an example, on 19 March, after sweeping Libya and Egypt, a huge dust storm reached Saudi Arabia and severely disrupted daily life, especially air and ground transportation as a result of a dramatic decrease in visibility. It was named Madar by the Committee for Naming Saudi Climate Conditions. Afterwards, on 20 March, the dust storm also affected other countries in the region including Iraq, Kuwait and Iran.

In the deserts of Central Asia, Mongolia and China, dust activity has not deferred substantially from that of the reference period. An episode that began on 3 May in the Gobi Desert and that affected much of East Asia is described in a later section of this Bulletin.

As described in the previous paragraphs, significant differences have been found at a regional scale between the estimated dust load in 2017 and the average value of the reference period 2003–2016. However, once the values are integrated spatially, the globally averaged dust AOD for 2017 (0.029) turns out to be very similar to those of previous years (Figure 3) and the inter-annual differences are much lower than the uncertainty inherent in the estimation. The studies analyzing long-term trends in dust emission have so far led to widely differing results (Tegen, 2016).

April: Dust episode in the Eastern and South-eastern Caribbean

Significant amounts of Saharan dust travel across the northern tropical Atlantic to the Caribbean every year. It is not unusual that within those plumes dust concentrations exceed World Health Organization (WHO) standards for particulate matter of 2.5 microns or less and 10 microns or less ($PM_{2.5}$ and PM_{10}) which could have serious implications

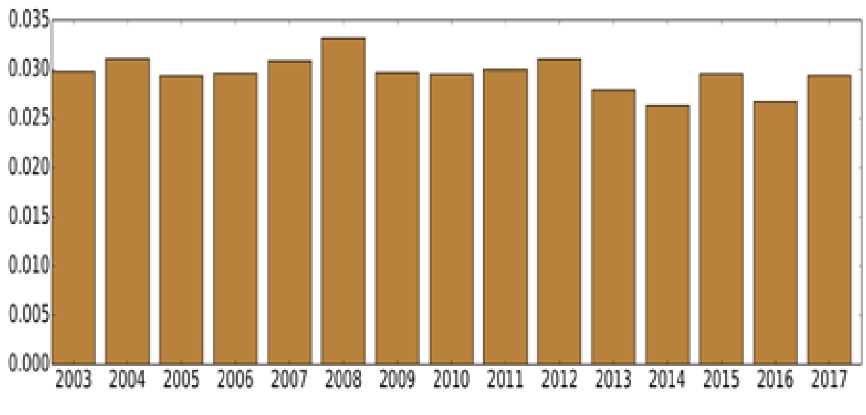

Figure 3. Annual global average of dust AOD

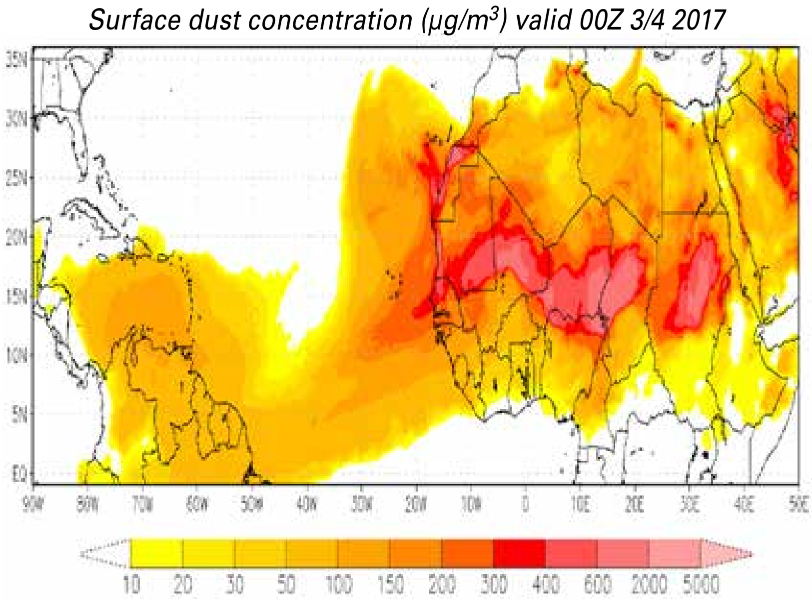

Figure 4. WRF-Chem surface dust concentration seven-day forecast issued March 27th, valid April 3rd 00Z

for human health in the impacted region. However, several territories in the Caribbean do not have routine air quality monitoring programmes nor do they enforce air quality standards for particulate matter.

Within the past two years, the **Caribbean Institute for Meteorology and Hydrology** (CIMH) has begun providing dust, $PM_{2.5}$, PM_{10} and ozone (O_3) concentration seven-day forecasts for the Caribbean using the advanced **Weather Research and Forecasting model coupled with Chemistry** (WRF-Chem). This section describes the CIMH WRF-Chem predictions of dust concentration and PM_{10} for an early April 2017 dust episode that affected Eastern and South-eastern Caribbean. The episode began on 1 April with the peak dust incursion occurring around 3–4 April. It garnered significant public attention, particularly because many Caribbean citizens have become increasingly aware of the potential impacts of airborne desert dust on air quality, and consequently, public health.

The WRF-Chem seven-day dust concentration forecast issued on March 27th (Figure 4) showed a significant dust outbreak predicted for April 3, 2017, across the Eastern and South-eastern Caribbean with relatively high concentrations of about 50–150 µg/m^3. These high concentrations of dust were confirmed by surface station observations in the South-eastern Caribbean (not shown). They exceeded the WHO guidelines for 24-hour mean PM_{10} of 50 µg/m^3. Furthermore, the peak of the PM_{10} observations from François, Martinique (Figure 5) coincided with the peak PM_{10} predicted by WRF-Chem. This maximum PM_{10} concentration also coincided with the timing of the dust incursion. Additionally, AERONET (Figure 6) and satellite retrievals of AOD confirmed high levels of dust over the region.

The CIMH WRF-Chem model accurately predicted the dust episode seven days in advance and the associated PM_{10} concentration. This makes the model a very useful tool for forecasting dust events and the associated decline in air quality as indicated by PM_{10} concentration. Predictions from other dust forecasting models as well as measurements from the **Caribbean Aerosol-Health Network** (CAHN) will be delivered in the future by the WMO SDS-WAS Regional Center for Pan-America.

May: severe dust event in East Asia

On 3 May, a deep cyclone centred in the eastern part of Mongolia triggered strong winds over the Gobi, a vast desert that stretches between Southern Mongolia and the Chinese region of Inner Mongolia. The strong winds raised large amounts of soil dust to the atmosphere and caused a severe dust storm that affected more than ten provinces in China. The dust cloud expanded and moved rapidly eastward. Between 5 and 7 May it reached the Korean Peninsula and Japan, and later the Northern Pacific.

Airborne dust caused a dramatic decline of air quality with very high dust concentrations registered by many stations, especially in the Inner Mongolia Autonomous Region of China, with peak hourly PM_{10} values over 2 000 µg/m^3. On 4 May, the storm reached Beijing, where the visibility dropped as low as 1 km and most monitoring stations showed PM_{10} readings of more than 1 000 µg/m^3

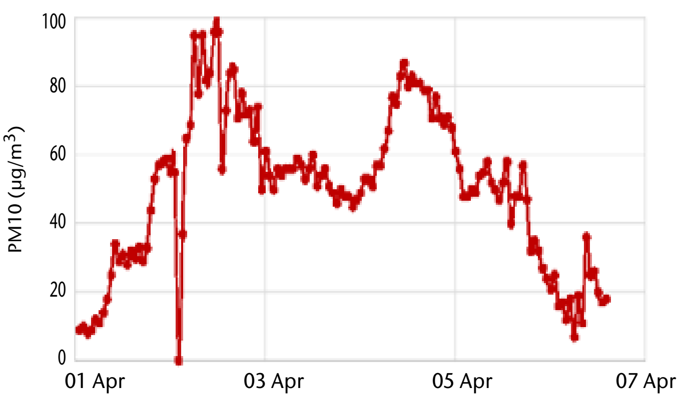

Figure 5. April 1st – 6th. PM_{10} measurements in µg/m^3 from François, Martinique, at local time

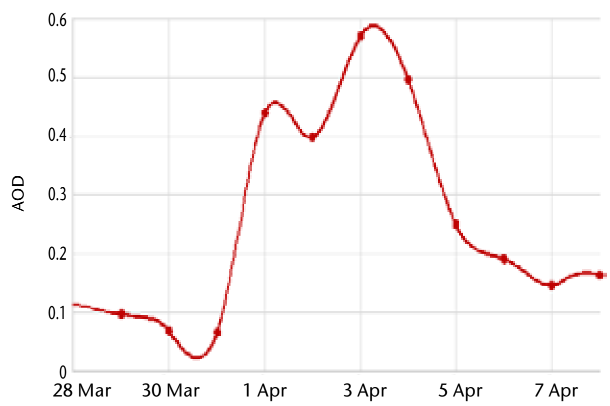

Figure 6. AERONET retrievals of AOD in Barbados – Ragged Point station

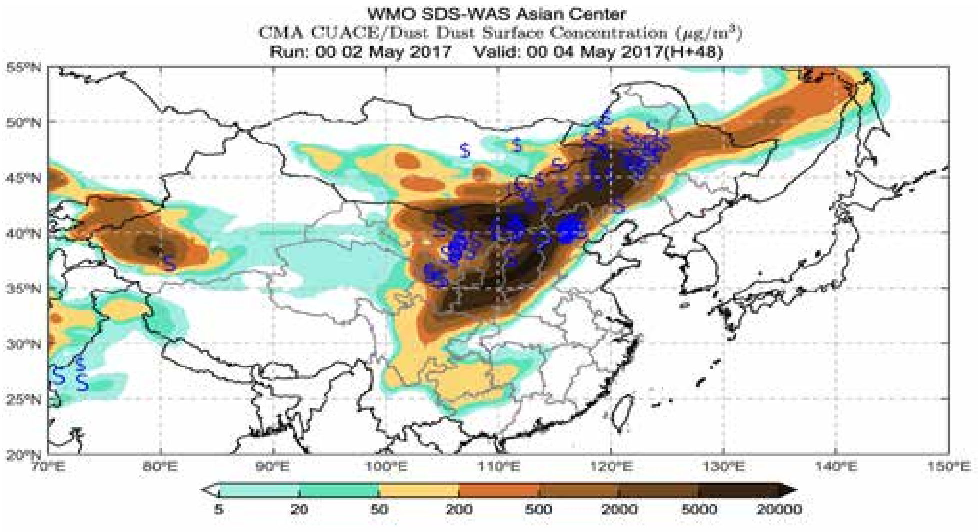

Figure 7. 48-hour forecast of dust surface concentration valid for 4 May 2017 at 00 UTC. Blue symbols indicate the weather stations where dust was recorded.

for the first time since 15 April 2015, though they dropped later in the day. These high concentrations caused the maximum value of 50 μg/m^3 recommended by the WHO air quality guidelines (WHO and UNAIDS, 2006) as a 24-hour mean to be widely exceeded. Officials urged residents of affected regions to avoid outdoor activities as much as possible, especially old people and children, in the first dust alert of 2017. Many pedestrians in downtown Beijing were later seen wearing protective masks and bandanas. The Beijing Capital International Airport reported that 48 flights were cancelled early morning, including six international routes.

Dust reached the Korean Peninsula in the evening of 5 May. The PM_{10} measurements peaked at hourly averages around 420 μg/m^3 in Baengnyeongdo and Gyegryelbi-do during the early morning hours of 6 May. Then, on 7 May, the dust cloud stretched over a wide area from Western to Northern Japan and parts of the Kanto region.

The dust episode was accurately forecast by the models contributing to the SDS-WAS Asian Center. Figure 7 shows good agreement between the shape of the dust plume forecasted by the China Meteorological Administration and dust records at weather stations.

Also in May 2017, in view of the demand of many national meteorological and hydrological services of the region and the good results obtained by the SDS-WAS, the WMO Executive Council designated **China Meteorological Administration** to host an operational centre in Beijing to routinely generate and distribute dust forecasts for Asia.

High-latitude dust

Cold climates are often associated with sparse vegetation, barren surfaces and above-average wind speeds. These conditions cause low retention of water on the surface and great erosion, resulting in large desertified areas. Cold deserts can be found in all continents, and together they cover about half of the Sahara desert extent. In the polar regions – latitudes over 50°N and 40°S – dust sources are often found in dried riverbeds and lakes while extremely active dust sources are close to glaciers and in glacial riverbeds and floodplains. Such active **High Latitude Dust** (HLD) sources are estimated to span at least 500 000 km^2 (Bullard et al., 2016) including areas of the northern (Alaska (USA), Canada, Greenland (Denmark), and Iceland) and southern (Antarctica, New Zealand, and Patagonia (Argentina)) hemispheres. All together those emit 80–100 Tg per year and contribute to about 5% of the global dust burden.

The location of many HLD sources is found in the vicinity of large glaciers, areas of snow and sea ice, where dust suspension and deposition can cause albedo reduction and, therefore, affect the climate (Meinander et al., 2016). Field experiments indeed have shown that Icelandic volcanic dust has similar effects on snow albedo and melting as black carbon (Peltoniemi et al., 2015).

Iceland is one of the best-studied HLD regions. About 44 000 km^2 of its territory is covered with deserted areas, which makes it the largest Arctic and European desert. Frequent dust events, an annual average of 135 days, transport particles long distances, sometimes over 1 000 km, towards the Arctic and Europe (Dagsson-Waldhauserova et al., 2014): about 7% of the emitted dust is deposited in the High Arctic (over 80° N latitude) and about 3% contributes to deposition in Europe. Dust particles in Iceland are different in size, colour and chemical composition to low-latitude crustal dust. Icelandic dust is very fine, dark in colour and rich in volcanic glass. $PM_1/PM_{2.5}$ ratios over 0.9 and PM_1/PM_{10} ratios of 0.34–0.63 are more similar to those of urban air pollution than to those of crustal dust.

Several large dust plumes from HLD sources were captured on satellite images in 2017. Autumn dust storms were frequent in Alaska. In particular, a large dust plume, over 300 km long and about 100 km wide, was captured by the MODIS spectroradiometer flying onboard NASA's Terra and Aqua satellites between 16 and 18 November (Figure 8).

EUMETSAT RGB-Dust product

There are many complementary ways of monitoring dust. Satellite products have the advantages of large spatial coverage (regional to global) and regular observations,

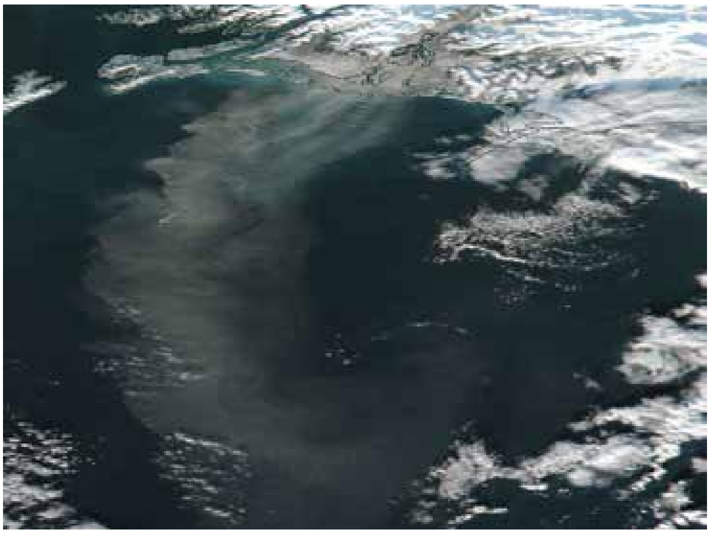

Figure 8. Aqua/MODIS true colour image of a dust plume south of the coast of Alaska on 18 November 2017

which can be made available to weather centres and other institutions in near-real-time. 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 high-resolution infrared spectrometers and interferometers on polar-orbiting satellite platforms have the potential to provide good quality dust information, but they present it with insufficient time resolution. The latest generation of satellites provide a vital tool for real-time dust monitoring: they combine the specific advantages of geosynchronous orbits (high time resolution over a wide geographic domain) with the geometric, radiometric and spectroscopic capabilities of high-resolution radiometers.

Multispectral products are generated from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument on the geostationary **Meteosat Second Generation** (MSG) satellite and operationally implemented to address a number of forecast challenges for both daytime and night-time applications. Referred to as "RGB Imagery" or "RGB Products", brightness temperatures or paired band differences are used to set the red, green, and blue intensities of each pixel in the final image, resulting in a false-colour composite. In particular, the **EUMETSAT MSG dust product** is based upon three infrared channels of SEVIRI. It is designed to monitor the evolution of dust storms over deserts during both day and night. Emissions and subsequent transport of individual dust events can be very well observed and followed in the RGB composite pictures. The full disc view includes the whole of Europe, all of Africa and the Middle East and allows frequent sampling, every 15 minutes, with a spatial resolution of 3 km in the nadir, enabling monitoring of rapidly evolving events. This aids the weather forecaster in the swift recognition and prediction of hazardous dust events.

In 2016, **EUMETSAT** relocated Meteosat-8, the first unit of MSG satellites, to 41.5°E, for the continuation of the Indian Ocean data coverage. It allows generation of the RGB-Dust product for West Asia (Figure 9), a region where the coverage was deficient through the MSG satellites centred on 0°.

The products generated from images captured by both units of MSG are available on the EUMETSAT website. They can also be found on the website of the SDS-WAS Regional Center for Northern Africa, Middle East and Europe, where, in addition, an archive that is accessible online is maintained.

Since a few months ago, similar products are generated from imagery captured by other geosynchronous satellites (Himawari-8 and GOES-16). **Himawari 8** is the 8th of the Himawari geostationary weather satellites operated by the **Japan Meteorological Agency**. It entered operational service in July 2015. The primary instrument aboard Himawari 8 is a multispectral imager designed to capture visible and infrared images of the Asia-Pacific region. On the other hand, **GOES-16** is the first of the GOES-R series of Geostationary Operational Environmental Satellite (GOES) operated by the U.S. **National Oceanic and Atmospheric Administration**. Its Advanced Baseline Imager provides atmospheric and surface measurements of America and the Atlantic Ocean. The RGB products from Himawari-8 and GOES-16 are available at the **SLIDER** webpage of the **Colorado State University**.

International Network to Encourage the Use of Monitoring and Forecasting Dust Products

Over the last few years, numerical prediction and observational products from ground and satellite platforms have become prominent at several research and operational weather centres due to growing interest from diverse stakeholders, such as solar power plant managers, health professionals, aviation and policymakers. Current attempts to transfer tailored products to end users are not coordinated, and the same technological and social obstacles are tackled individually by all different groups, a process that makes the use of data slow and expensive.

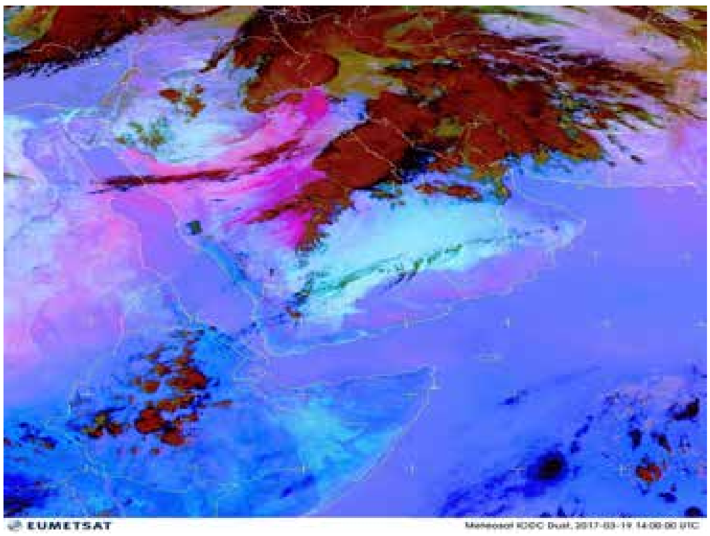

Figure 9. The EUMETSAT RGB-Dust product for 19 March 2017 at 14 UTC shows the Madar duststorm affecting Iraq and the Arabian Peninsula

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To soothe this situation, an international consortium participates in the EU-COST Action **International Network to Encourage the Use of Monitoring and Forecasting dust Products** (InDust). InDust started in November 2017 and will span four years. COST is an EU-funded programme that enables researchers to set up their interdisciplinary research networks in Europe and beyond. COST provides funds for organizing conferences, meetings, training schools, short scientific exchanges or other networking activities in a wide range of scientific topics.

InDust has the overall objective to establish a network involving research institutions, service providers and potential end users of information on airborne dust. InDust searches to coordinate and harmonize the process of transferring dust observation and prediction data to users as well as to assist the diverse socio-economic sectors affected by the presence of high concentrations of airborne mineral dust. These objectives are well aligned with the mission of the WMO SDS-WAS and, therefore, close coordination between both initiatives is expected.

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Contacts

WMO SDS-WAS:

http://www.wmo.int/sdswas
e-mail: abaklanov@wmo.int

WMO SDS-WAS Regional Center for Northern Africa, Middle East and Europe:

http://sds-was.aemet.es
e-mail: sdswas@aemet.es

WMO SDS-WAS Regional Center for Asia:

http://eng.nmc.cn/sds_was.asian_rc
e-mail: xiaoye@camscma.cn

WMO SDS-WAS Regional Center for the Americas:

http://sds-was.cimh.edu.bb/
e-mail: dfarrell@cimh.edu.bb

Editorial board

Other contributors to this issue

Sara Basart, Pavla Dagsson-Waldhauserova, Gerardo García-Castrillo and Ashford Reyes

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