AIRBORNE DUST: FROM R&D TO OPERATIONAL FORECAST

2013-2015 Activity Report of the SDS-WAS Regional Center for Northern Africa, Middle East and Europe

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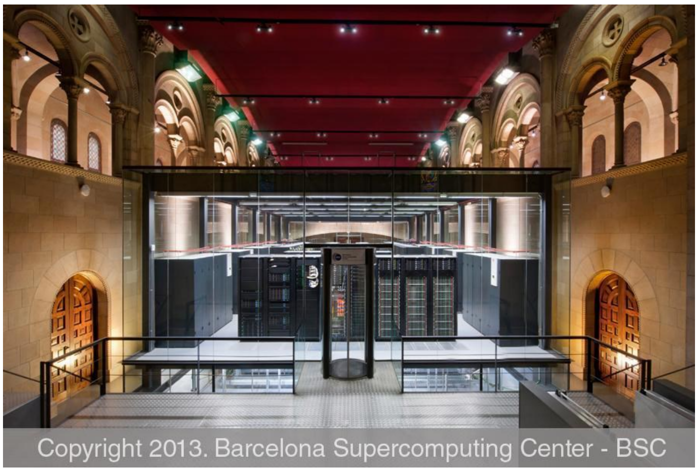

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Cover photograph: *Sand storm on road N11 in Niger between Agadez and Zinder (photo A. Backer).*

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FOREWORD

In the rapidly changing world the role of research and development is increasing. Advances in atmospheric sciences drive the development of new products and services that increase the resilience and preparedness of society to environmental extremes. The World Meteorological Organization (WMO) through the Global Atmosphere Watch (GAW) Programme, the World Weather Research Programme (WWRP) and the co-sponsored World Climate Research Programme (WCRP) provides leadership in research related to atmospheric environment, weather and climate. The GAW Programme focuses on atmospheric composition changes, and its attribution to natural and anthropogenic processes, while WWRP advances society's ability to cope with high impact weather through research focused on improving the accuracy, lead time and utilization of weather prediction. As many environmental problems are cross-cutting in nature, GAW and WWRP jointly work on a number of such projects that require combining atmospheric composition and weather research. The WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) is one of the most successful examples that demonstrates the important chain from Research to Operation services.

In many regions of the world, sand and dust storms constitute a significant environmental hazard with negative impacts on human health, agricultural production, and transport security, amongst many others. A number of decisions and actions have recently taken place to address this phenomenon at international level, including a request from the United Nations General Assembly (2015) to develop the “Global Assessment of Sand and Dust Storms”[1]. WMO plays a prominent role in these international activities.

At the request of forty WMO Members to improve their capabilities for more reliable sand and dust storm forecasts, the WMO Sand and Dust Storm Project was implemented in 2004 and its Sand and Dust Storm Warning Advisory and Assessment System[2] (SDS-WAS) in 2007. SDS-WAS enhances the ability of countries to deliver timely, quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities. Under the leadership of the WMO SDS-WAS Steering Committee, two SDS-WAS Regional Nodes namely: (i) Northern Africa, Middle East and Europe (NAMEE),

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[1] The report was jointly produced by the UN Convention to Combat Desertification (UNCCD), the United Nations Environmental Programme and WMO, full text available at http://uneplive.unep.org/media/docs/assessments/global_assessment_of_sand_and_dust_storms.pdf

[2] www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html

coordinated by a Regional Center in Barcelona, Spain and hosted by the State Meteorological Agency (AEMET) and the Barcelona Supercomputing Center (BSC); (ii) Asian node, coordinated by a Regional Center in Beijing, China, that is hosted by the China Meteorological Administration (CMA), are providing SDS forecasts to respective regions. Two other regional nodes covering America and Western Asia are at different stages of establishment.

The 17th World Meteorological Congress endorsed the Barcelona Supercomputing Center as the first WMO Regional Meteorological Center specialized on Atmospheric Sand and Dust Forecast (Barcelona Dust Center). This decision recognizes the valuable contribution of AEMET and BSC consortium towards the production of excellence research and the creation of specialized products for the end-users. The services provided by the Barcelona Dust Center allow for the development of strategies to minimize severe impacts caused by atmospheric dust on lives and property in Northern Africa, Middle East and Europe.

It is my pleasure to present this report summarizing the activities of the SDS-WAS Regional Center for Northern Africa, Middle East and Europe for 2013-2015 and showing the great success of the SDS-WAS project.

Dr Deon Terblanche

Director of the Atmospheric Research and Environment (ARE) Branch Research Department

World Meteorological Organization

1. Introduction

1.1. The dust cycle

Each year, wind lifts large amounts of mineral dust into the atmosphere over the world’s arid regions. Aeolian erosion is the main physical process that incorporates solid particles into the atmosphere and mineral dust, along with sea salt, the largest contributor to atmospheric aerosol at a global scale (Chin et al., 2009).

The dust release is associated to diverse meteorological systems, from short-lived micro-scale dust devils to persistent continental-scale circulation systems causing an increase in wind speed over a wide area. The main sources of mineral dust are located in the arid regions of Northern Africa, the Arabian Peninsula, Central Asia and China, although there are also significant contributions from Australia, North America and South Africa. Global estimates of dust emissions, very uncertain and mainly derived from modelling approaches, range between 1 and 2.2 Gigatons per year (Zender et al., 2004).

Once released, fine dust particles can be raised to high altitudes by turbulence and up-drafts and then transported thousands of kilometres across the globe. Dust particles are removed from the atmosphere by gravitational settling, impaction, turbulence, in-cloud scavenging or precipitation. The particle size of mineral dust is generally considered to be in the range spanning from less than 1 µm to about 100 µm. Its lifetime in the atmosphere ranges from a few hours for particles larger than 10 µm, to more than 10 days for the sub-micrometric ones (Tegen and Lacis, 1996).

Figure 1: Sand storm on road N11 in Niger between Agadez and Zinder (photo A. Backer)

1.2. Dust sources in Northern Africa, Middle East and Europe

The Sahara is the first global source of dust in the world, accounting approximately for half of the mineral dust mobilized globally (Goodie and Middleton, 2001). Most of its emissions are considered natural, since desert soils are not significantly modified by anthropic activity. About 100 Megatons of Saharan dust are estimated to be annually transported to Europe. However, the main transport route leads to the Atlantic, sometimes reaching the Caribbean Sea after a travel of 5 to 7 days (Prospero and Nees, 1986). Other portions of Saharan dust are directed to the Middle East and the Gulf of Guinea. In the neighbouring Sahel, dust emission is mainly related to soils disturbed by overgrazing, cultivation and, especially along the Senegal and Niger riverbanks, deforestation. Anthropogenic sources can also be found along the Mediterranean coast of Africa.

The main dust sources in the Middle East are Mesopotamia, especially the region between the Tigris and Euphrates rivers, and the highlands of central Saudi Arabia, although a large number of small sources have been identified in much of the region (Hamidi et al., 2012). The construction of dams and the diversion of river water for irrigation and domestic use has greatly reduced river flow and is the main cause of the desiccation of lakes and wetlands such as the Aral sea, the Urumia lake or the Mesopotamian marshes. This process has led in recent years to a sharp increase in the frequency and intensity of dust storms in the region.

Dust emission is also observed in southern European regions such as Andalusia and Cyprus, especially in summer (Ginoux et al., 2012), Although to a much lesser extent than in Northern Africa or the Middle East,

1.3. Dust impacts

Even though airborne dust is a minor element of the atmospheric composition, it plays a key role in different aspects of weather and climate dynamics (Nickovic et al., 2004; Pérez et al., 2006; Wang et al., 2010): the Earth’s radiative budget, cloud microphysics and precipitation, and atmospheric chemistry. Nonetheless, as stressed by the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013), the level of scientific understanding of the effects of aerosol on climate is still low.

For countries located in or in the vicinity of arid regions, airborne dust presents serious risks to the environment, property and human health. Many studies have demonstrated an association between particulate matter exposure and the exacerbation of cardiovascular and respiratory disease and resulting mortality. However, few studies have dealt with the specific effect of natural dust particles. De Longueville et al. (2013) provide a literature review of scientific publications in the period 1999-2011 aiming to learn more about the relationship between desert dust and human health around the world. The factors determining the dust impact on human health may include intensity and duration of the exposure, particle size and composition, and pathogens present in the material. The particles larger than 10 μm are not breathable and, therefore, can only cause damage to external organs, such as eye irritation and infection. Particles with a diameter smaller than 10 μm are referred to as inhalable particles. Most of them are trapped within the nose, mouth and upper respiratory tract. However, the finest ones may penetrate into the lower respiratory tract until the alveolar region, being incorporated into the bloodstream and therefore affecting any organ of the body. Regarding the dust chemical composition, several studies have associated the presence of metals with a variety of toxicity effects including oxidative stress, inflammatory responses and cancer. Finally, there is compelling evidence of a link between dusty conditions and meningococcal meningitis in Sub-Saharan Africa (Molesworth et al., 2003; Pérez et al., 2014). It has been suggested that the impact of dust particles may damage the mucosa in the nose and throat, thus providing a portal of entry for the bacteria (Dukic et al., 2012). Moreover, iron oxides embedded in dust particles are suspected to enhance chances for the infection (Thompson et al, 2013).

Figure 2: Line for meningitis vaccination in Arua, Uganda (photo S. Gosh)

Significant dust events have a substantial impact on air traffic through visibility reduction. Poor visibility conditions pose a risk to aircraft landing and taking off operations and can lead to diverted flights, delayed departures and airport operational problems. On the other hand, reduced radiation at the surface has an impact on the output from solar power plants, especially those that rely on direct solar radiation. However, dust deposition over the collectors is the main concern of the plant operators. Keeping the solar collectors dust-free to prevent particles from blocking incoming radiation requires laborious and costly maintenance.

When deposited on the surface, dust interacts with continental and maritime ecosystems constituting a source of micronutrients for them. It has been hypothesised that the Amazon rainforest is fertilised significantly by Saharan dust and that dust transport of iron positively affects marine biomass production in parts of the world oceans suffering shortage of this metal (Bristow et al., 2010).

1.4. The Sand and Dust Storm - Warning Advisory and Assessment System

In May 2007, owing the societal needs for monitoring and forecasting dust events, and for assessing and mitigating their negative impacts, the 14th Congress of the **World Meteorological Organization** (WMO) endorsed the launching of the **Sand and Dust Storm - Warning Advisory and Assessment System** (SDS-WAS) with the mission to enhance the ability of countries to deliver timely and quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities (Terradellas et al., 2015a).

The SDS-WAS works as an international hub of research, operational centres and end-users, organized through regional nodes. At the level of nodes, SDS-WAS is structured as a federation of partners. A federated approach allows flexibility, growth and evolution, while preserving the autonomy of individual institutions. Activities within each node are led by a SDS-WAS Regional Steering Group (RSG) and coordinated by a Regional Centre (Figure 3).

Two nodes are currently in operation:

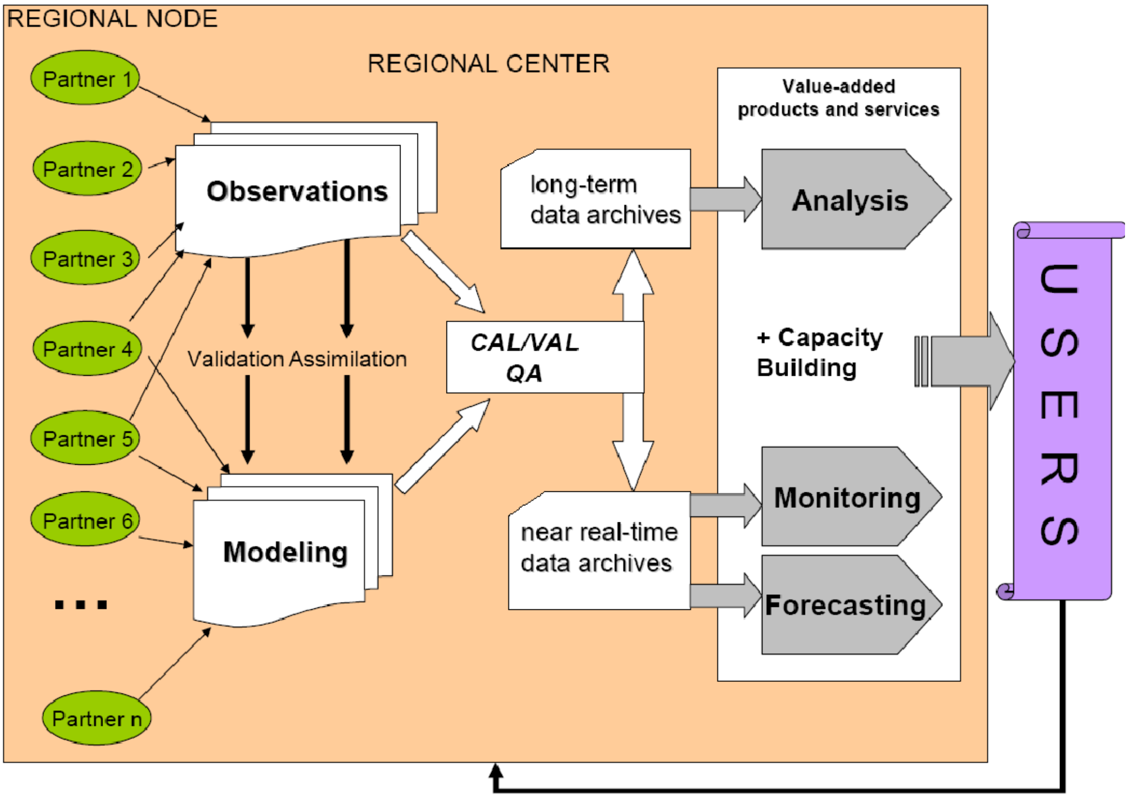


Figure 3: Flow of information between the SDS-WAS regional components

- **Regional Node for Asia**, coordinated by a Regional Center in Beijing, China, hosted by the China Meteorological Administration (CMA).
- **Regional Node for Northern Africa, Middle East and Europe**, coordinated by a Regional Center in Barcelona, Spain, hosted by the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Center - National Supercomputing Center (BSC). The composition of the RSG for Northern Africa, Middle East and Europe as at 31 December 2015 is listed in 1.

Member	Institution
Slobodan NICKOVIC (chair)	Republic Hydrometeorological Service of Serbia, Serbia
José María BALDASANO (Regional Center)	Barcelona Supercomputing Center, Spain
Emilio CUEVAS-AGULLO (Regional Center)	State Meteorological Agency of Spain, Spain
Angela BENEDETTI	European Centre for Medium-Range Weather Forecast
Malcolm BROOKS	Met Office, U. K.
George KALLOS	University of Athens, Greece
Benjamin LAMPTEY	African Centre of Meteorological applications for Development
Lucia MONA	National Research Council, Italy
Goran PEJANOVIC	Republic Hydrometeorological Service of Serbia, Serbia
Michael SCHULZ	Norwegian Meteorological Institute, Norway
Ina TEGEN	Leibniz Institute for Tropospheric Research, Germany
Ashraf ZAKEY	Egyptian Meteorological Authority, Egypt
Alexander BAKLANOV	World Meteorological Organization

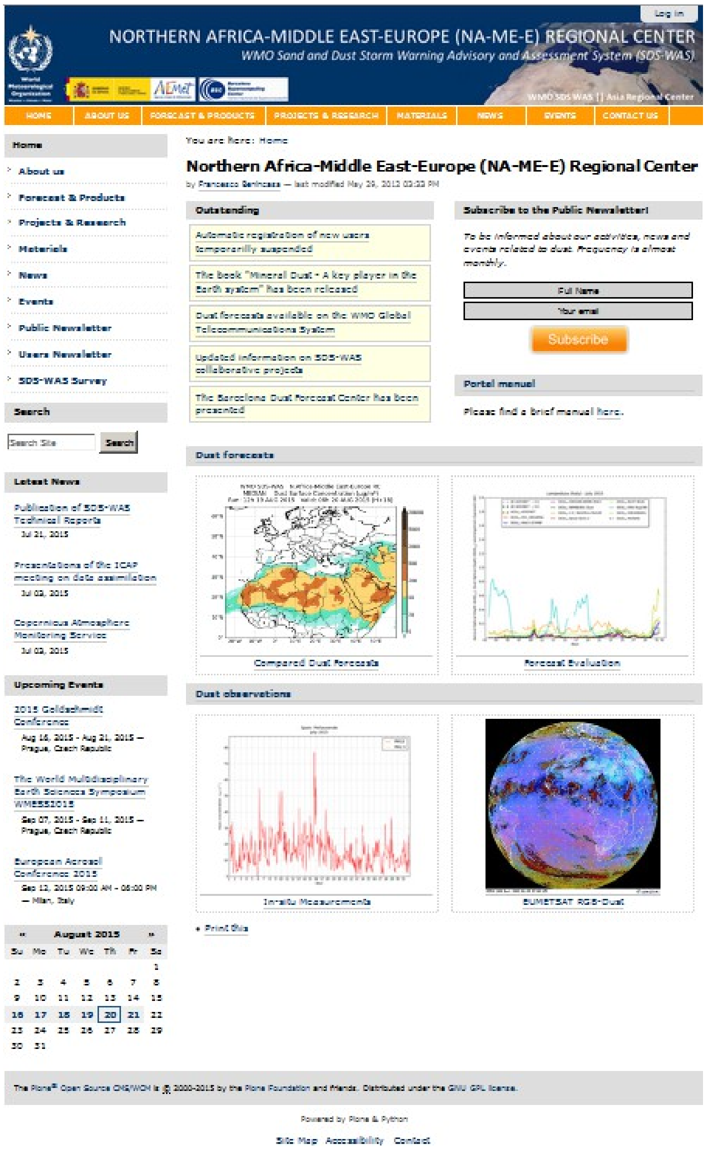
Table 1: Composition of the SDS-WAS Regional Steering Group for Northern Africa, Middle East and Europe as at 31 Dec 2015

2. SDS-WAS Regional Center for Northern Africa, Middle East and Europe. Preliminary activity 2010-2012

The WMO SDS-WAS **Regional Center for Northern Africa, Middle East and Europe** was established in April 2010 to coordinate SDS-WAS activities within this region. The Centre, as a consortium of AEMET and the BSC, soon evolved into a structure that hosted international and interdisciplinary research cooperation between numerous organizations in the region and beyond, including national meteorological services, environmental agencies, research groups and international organizations. Its initial activity is described at the Regional Center Activity Report 2010-2012 (Terradellas et al., 2014).

2.1. Design and implementation of the web portal

The web portal of the Regional Center (http://sds-was.aemet.es, Figure 4) was designed to allow users access to observational and forecast products, as well as to sources of basic information. In particular, the portal provides National Meteorological and Hydrological Services (NMHSs) with the necessary information to issue operational predictions and warning advisories related to dust content in the atmosphere. The site became fully operational in 2010. Since then, efforts have been aimed to progressively increase the amount and quality of the content published, with special emphasis on observational and forecast products.



You are here: Home

Northern Africa-Middle East-Europe (NA-ME-E) Regional Center

by Francesco Benincasa — last modified May 29, 2013 03:23 PM

Outstanding

Automatic registration of new users temporarilly suspended

The book "Mineral Dust - A key player in the Earth system" has been released

Dust forecasts available on the WMO Global Telecommunications System

Updated information on SDS-WAS collaborative projects

The Barcelona Dust Forecast Center has been presented

Subscribe to the Public Newsletter!

To be informed about our activities, news and events related to dust. Frequency is almost monthly.

Portal manual

Please find a brief manual here.

Dust forecasts

Compared Dust Forecasts

Forecast Evaluation

Dust observations

Insitu Measurements

EUMETSAT RGB-Dust

Latest News

Publication of SDS-WAS Technical Reports
Jul 21, 2015

Presentations of the ICAP meeting on data assimilation
Jul 03, 2015

Copernicus Atmosphere Monitoring Service
Jul 03, 2015

Upcoming Events

2015 Goldschmidt Conference
Aug 16, 2015 - Aug 21, 2015 — Prague, Czech Republic

The World Multidisciplinary Earth Sciences Symposium WMESS2015
Sep 07, 2015 - Sep 11, 2015 — Prague, Czech Republic

European Aerosol Conference 2015
Sep 12, 2015 09:00 AM - 06:00 PM — Milan, Italy

«	August 2015					»
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Figure 4: Home page of the Regional Center web portal: http://sds-was.aemet.es

2.2. Joint visualization and evaluation of numerical dust models

The exchange of forecast products is the basis for model inter-comparison and joint evaluation. At the end of 2012, seven modelling groups provided numerical predictions, which were daily plotted side by side. Multi-model products based on the exchanged forecasts were also generated. Finally, a common evaluation was established in order to assess whether the modelling systems successfully simulate the temporal and spatial evolution of the dust-related parameters.

2.3. Sand and Dust Storm Africa

AEMET, in collaboration with WMO, has established a network of sun photometers in Northern Africa (Morocco, Algeria and Egypt) to detect and monitor dust storms.

Instruments have been installed at:

- Observatory of **Tamanrasset**, Algeria, in the core of the Sahara, where most airborne particles can be considered as mineral dust.
- Headquarters of the Egyptian Meteorological Authority in **Cairo**, Egypt, a strategic site to monitor and study the dust transport to the Mediterranean and also for investigating the interactions between natural dust and anthropogenic pollution.
- **Ouarzazate**, Morocco, on the South-eastern slopes of the Atlas, at the edge of the desert, a strategic site to monitor dust outbreaks over the North Atlantic.

Data from the three stations, which are part of the Aerosol Robotic NETwork (AERONET), are routinely used in the SDS-WAS joint evaluation of dust models.

Figure 5: Sun-photometer installed at the station of Tamanrasset, Algeria

2.4. Capacity building

One of the basic objectives of the Regional Center is to promote the use of dust-related products. For this purpose, the Center coordinates with partners and NMHSs in the region different actions aimed to strengthen the capacity of countries to use the observational and forecast products distributed in the framework of the WMO SDS-WAS. The events organized by the Regional Center in the period 2010-2012 were:

- **Training Week on Satellite Meteorology**, Barcelona, Spain, 8-12 November 2010.
- **Lectures on Atmospheric Mineral Dust and its Impact on Human Health, Environment and Economy**, Barcelona, Spain, 13 November 2010.
- **Training Week on WMO SDS-WAS Products**, Barcelona, Spain, 15-19 November 2010.
- **2nd Training Course on WMO SDS-WAS Products** (Satellite Observation and Modelling of Atmospheric Dust), Ankara, Turkey, 21-25 November 2011.

- **II Lectures on Atmospheric Mineral dust**, Barcelona, Spain, 5-9 November 2012.

Figure 6: Participants in the Training Week on WMO SDS-WAS Products

2.5. Towards a West Asian SDS-WAS Regional Node

Sand and Dust Storms are a major problem in West Asia, where their intensity, extent and frequency are not well characterized yet (Cuevas, 2013). The growing concern of countries in the region has led to a number of high-level international meetings. First, the Government of Turkey convened a meeting of the Ministers of the Environment of Turkey, the Islamic Republic of Iran, Iraq and the Syrian Arab Republic in Ankara in April 2010. The meeting proposed to launch a project to reduce the environment pollution by dust. Two subsequent meetings at both technical and ministerial levels were held in Tehran in September 2010 with the additional participation of Qatar. The agreements reached in these meetings formed the basis for building a regional sand and dust storm programme.

In November 2012, a Regional Conference on Dust and Dust Storms was held in Kuwait City. UNEP and WMO jointly organized a special session on scientific aspects of the planned regional sand and dust programme. The Conference agreed on the two following recommendations:

- WMO would conduct a survey to identify the existing sand and dust observing and forecasting facilities in the region.
- An SDS-WAS Regional Node for West Asia would be established, at the initiative of WMO, to satisfy needs for providing and improving observation and forecasting products.

3. SDS-WAS Regional Center for Northern Africa, Middle East and Europe. Activity 2013-2015

3.1. The WMO SDS-WAS

Once the SDS-WAS had been established, with two Regional Centres in operation, WMO wrote a new **Science and Implementation Plan** (SIP) for the period 2015-2020 (Nickovic et al., 2015). The document, approved in 2014, summarizes the milestones achieved to that date, describes the governance and future development plans and, above all, establishes priority research lines for the reference period, which are as follows:

- Model evaluation and inter-comparisons.
- High-resolution dust modelling.
- Data assimilation.
- Chemical and physical characterization of dust and its optical properties.
- Dust re-analysis.
- Dust interaction with radiation and clouds and impacts to weather and climate.
- Further dust impacts.
- Dust observation techniques and methodologies.

The SIP establishes that the SDS-WAS activities at the global scale will be coordinated by a **Steering Committee**, whose kick-off meeting was held in Amman, Jordan, on 6-7 November 2014. It was attended by representatives of the regional nodes and the WMO Secretariat. Enric Terradellas, from AEMET, technical director of the Regional Center for Northern Africa, Middle East and Europe, was elected chair of the Steering Committee for the next two years.

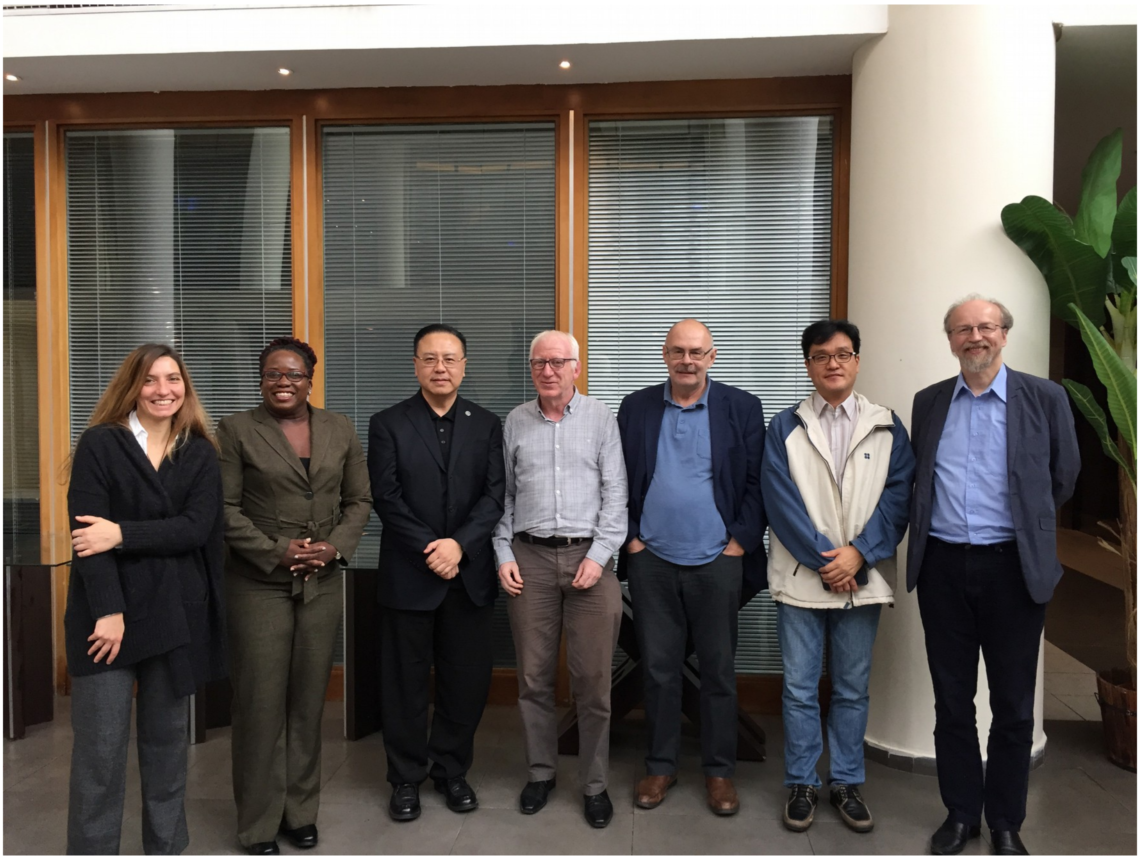

Figure 7: Participants in the kick-off meeting of the WMO SDS-WAS Steering Committee

The Steering Committee considers the establishment of the American node as one of the key objectives for the following months. A Regional Center is expected to be created in Barbados with the support of the Caribbean Institute for Meteorology and Hydrology (CIMH). The Center will focus primarily on the health effects of dust and its impact on the marine ecosystems. There has been less progress in the implementation of a Regional Center for West Asia, despite the excellent preliminary report of Cuevas (2013), prepared under the supervision of WMO and supported by United Nations Environment Programme (UNEP).

3.2. Web portal. Maintenance and publication of new products

Efforts have been aimed to progressively increase the amount and quality of the content published, with special emphasis on observational and forecast products.

A global observational network is crucial to any forecast and early warning system for real-time monitoring, validation and evaluation of forecast products, and data assimilation systems that may be developed in the future. The main data sources are in-situ aerosol measurements performed on air quality monitoring stations, indirect observations (visibility and present weather) from meteorological stations, and ground-based (lidar and photometers) and satellite remote-sensing products. Most observational products available on the web portal were already described on the Regional Center Activity Report 2010-2012 (Terradellas et al., 2014). The most important new releases are a monitoring product based on visibility, and updated information on lidar and ceilometers.

In-situ measurements of particulate matter concentration are systematic and with high spatial density in Europe, but very sparse, discontinuous and rarely near-real-time (NRT) available close of the main dust sources. Satellite products present global coverage. However, they usually integrate the content of all types of aerosol over the vertical column and do not provide information about the dust contents close to the ground. Since weather datasets have an excellent spatial and temporal coverage, visibility information included in meteorological observations can be used as an alternative proxy to monitor dust events. Visibility is mainly affected by the presence of aerosol and water in the atmosphere. Therefore, the use of visibility data has to be complemented with information on present weather to discard those cases where visibility is reduced by the presence of hydrometeors (fog, rain, etc.) or by particles of different nature. The maps published on the web identify the cases of visibility reduction by sand or dust to less than 5 km reported in METAR or SYNOP bulletins from more than 1,500 stations that are checked every 6 hours (Figure 8).

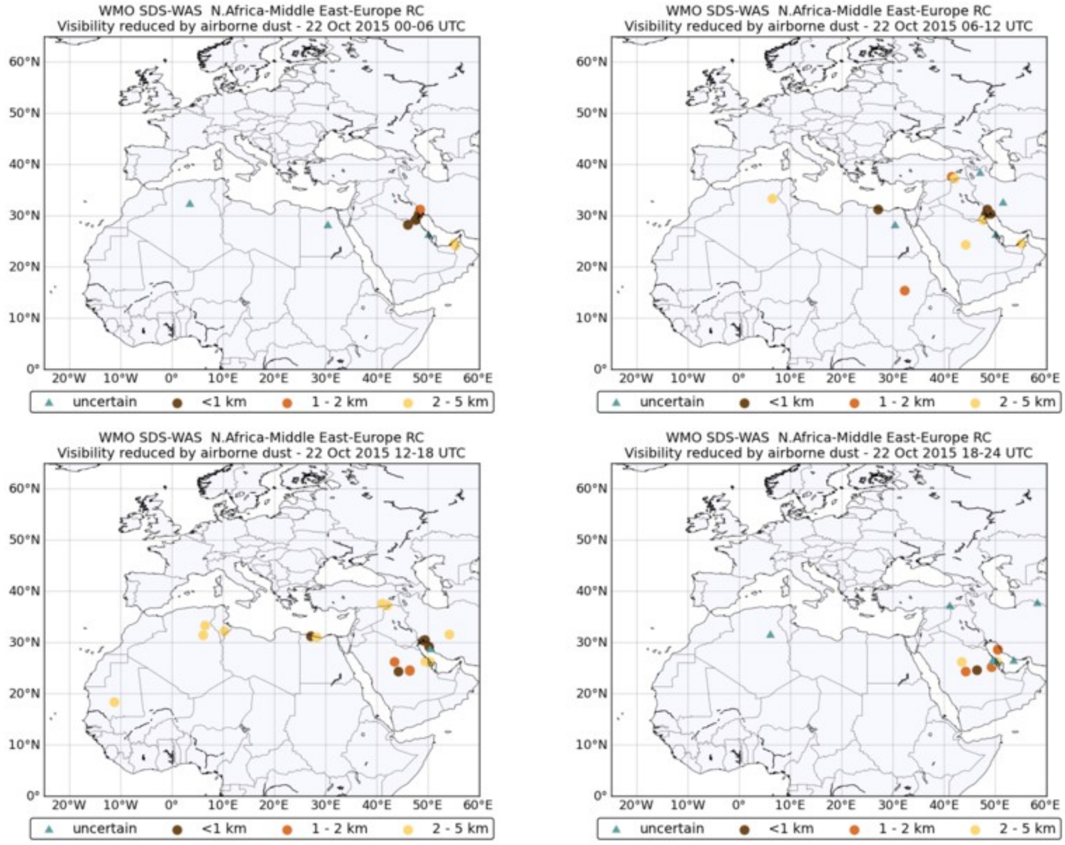

Figure 8: Stations where visibility has been reduced by sand and dust on 22 October 2015. Brownish circles indicate sites where 'sand' or 'dust' has been explicitly reported and triangles indicate stations where the present weather has been reported as 'haze', meaning that the visibility has been reduced by particles of unspecified origin.

LIDAR (Light Detection And Ranging) is a radar system using ultraviolet, visible or near-infrared light instead of microwaves or radio waves. Very short laser pulses of light are emitted into the atmosphere and partially scattered back to the lidar by the atmospheric gases or by particles suspended in the air. The position, concentration and some information on the properties of the scatters are determined from the backscattered energy and the time to return to the lidar telescope. The aerosol lidar systems estimate vertical profiles of particulate matter extinction from the backscatter profiles. Comparison of backscatter at different wavelengths provides some indication of particle size. Finally, if polarized light is used, the non-spherical character of particles can be determined: since dust particles are usually less spherical than other aerosol types, the method allows distinction between mineral dust and other pollutants. There are several lidar networks operating in the world. The web portal offers links to quick-looks and data from two of them:

- **European Aerosol Research LIdar NETwork** (EARLINET). It was the first aerosol lidar network, established in 2000, with the main goal to provide a comprehensive, quantitative, and statistically significant data base for the aerosol distribution on a continental scale (Bosenberg et al., 2003).
- **Micro-Pulse Lidar NETwork** (MPLNET). It is a federated network of Micro-Pulse Lidar (MPL) systems coordinated by NASA and designed to measure aerosol and cloud vertical structure continuously, day and night, over long time periods (Welton et al., 2001).

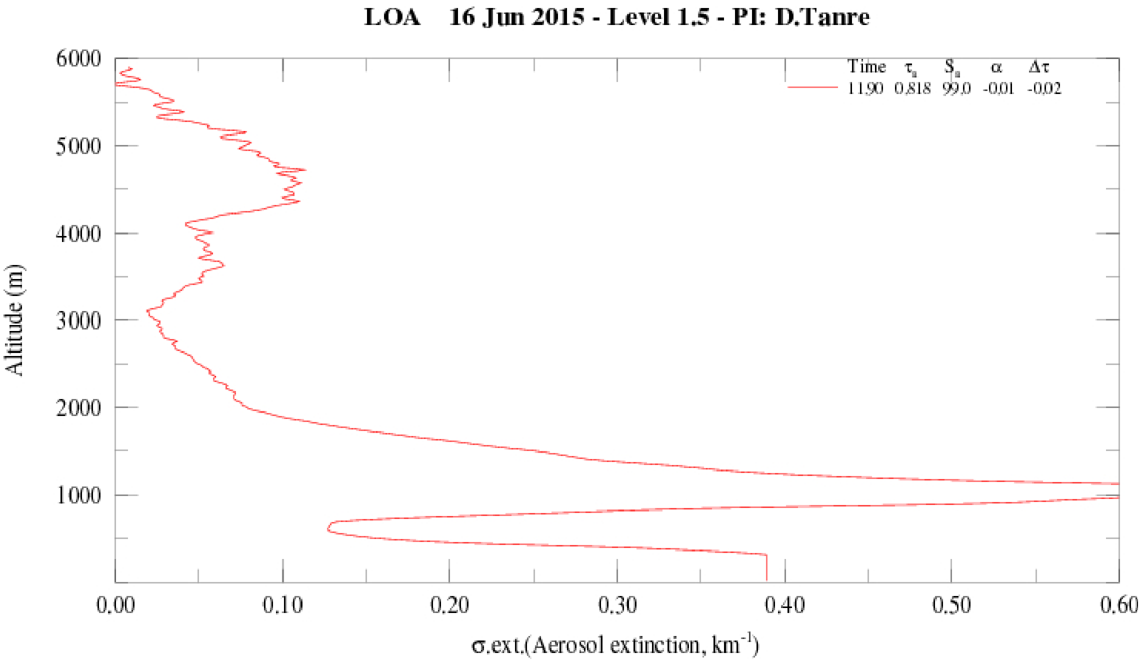

Figure 9: Retrieval of aerosol extinction from the MPL of N'Bour, Senegal, on 16 June 2016 at 11:54 UTC. The lidar is operated by the Lille-1 University

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, which is part of the A-train constellation, provides observations from space-borne lidar. It carries the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), which is a two-wavelength polarization-sensitive lidar that provides high-resolution vertical profiles of aerosols and clouds (Winker et al., 2004; 2007).

As for prediction products, much progress has been done in the joint visualization and evaluation of numerical dust models, as described in the next section. Moreover, it is noteworthy that the Regional Centre has begun to make the online datasets available to users. Numerical dust forecasts are distributed in NetCDF format. This format was developed and is maintained at Unidata, part of the U. S. University Corporation for Atmospheric Research (UCAR).

3.3. Joint visualization and evaluation of numerical dust models

The model inter-comparison and joint evaluation exercise has grown significantly with the incorporation of new partners. At the end of 2015, ten modelling groups (2) provide daily forecasts of dust surface concentration (DSC) and dust optical depth (DOD) at 550 nm for a reference area (RA) extending from 25°W to 60°E in longitude and from 0° to 65°N in latitude. This RA is intended to cover the main source areas in Northern Africa and Middle East, as well as the main transport routes and deposition zones from the equator to the Scandinavian Peninsula. The action involves forecasts up to 72 h with a 3-hour frequency.

Model	Institution
BSC-DREAM8b_v2	Barcelona Supercomputing Center, Spain
CAMS	European Centre for Medium-Range Weather Forecast, U. K.
DREAM-NMME-MACC	South East European Climate Change Center, Serbia
NMMB/BSC-Dust	Barcelona Supercomputing Center, Spain
MetUM	Met Office, U. K.
GEOS-5	National Aeronautics and Space Administration, U. S. A.
NGAC	National Centers for Environmental Prediction, U. S. A.
EMA/Reg-CM4	Egyptian Meteorological Authority, Egypt
DREAMABOL	National Research Council, Italy
WRF-CHEM	National Observatory of Athens, Greece

Table 2: Models contributing to the SDS-WAS model inter-comparison and forecast evaluation

The numerical forecasts that are not subject to legal restrictions can be downloaded from the Regional Center website. 3 shows the annual number of downloads for the multi-model median.

Year	Number of downloads
2014	841
2015	5,125

Table 3: Annual number of downloads for the multi-model median

The DSC and DOD forecasts are daily plotted side-by-side for the RA using a common colour palette and geographical domain. The plots (Figure 10) are routinely generated and made available at the end of each day using the results of the simulations starting the same day either at 00 or at 12 UTC. In this manner, forecasts released by the models are available for a common period of up to 48 hours, thus making the product a powerful tool to issue short-term predictions and early warning notices.

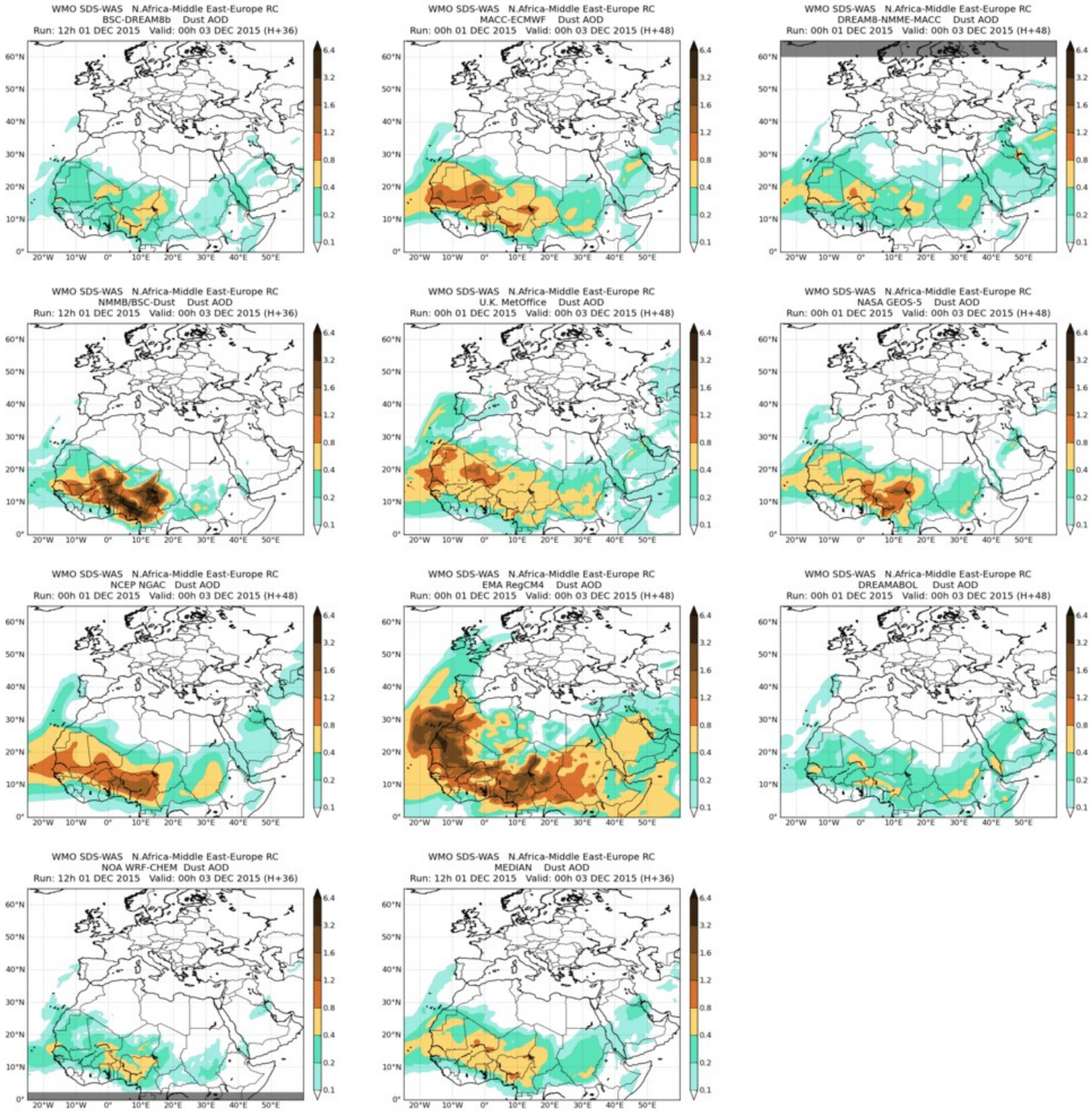

Figure 10: DOD forecasts released by ten models and the median of them for 00 UTC 3 December 2015

Ensemble multi-model products (Figure 11) are daily generated after bi-linearly interpolating all forecasts to a common grid mesh of 0.5 x 0.5 degrees. Multi-model forecasting intends to alleviate the shortcomings of individual models while offering an insight on the uncertainties associated with a single-model forecast. Centrality products (median and mean) are aimed at improving the forecasting skill of the single-model approach. Spread products (standard deviation and range of variation) indicate whether forecast fields are consistent within multiple models, in which case there is greater confidence in the forecast.

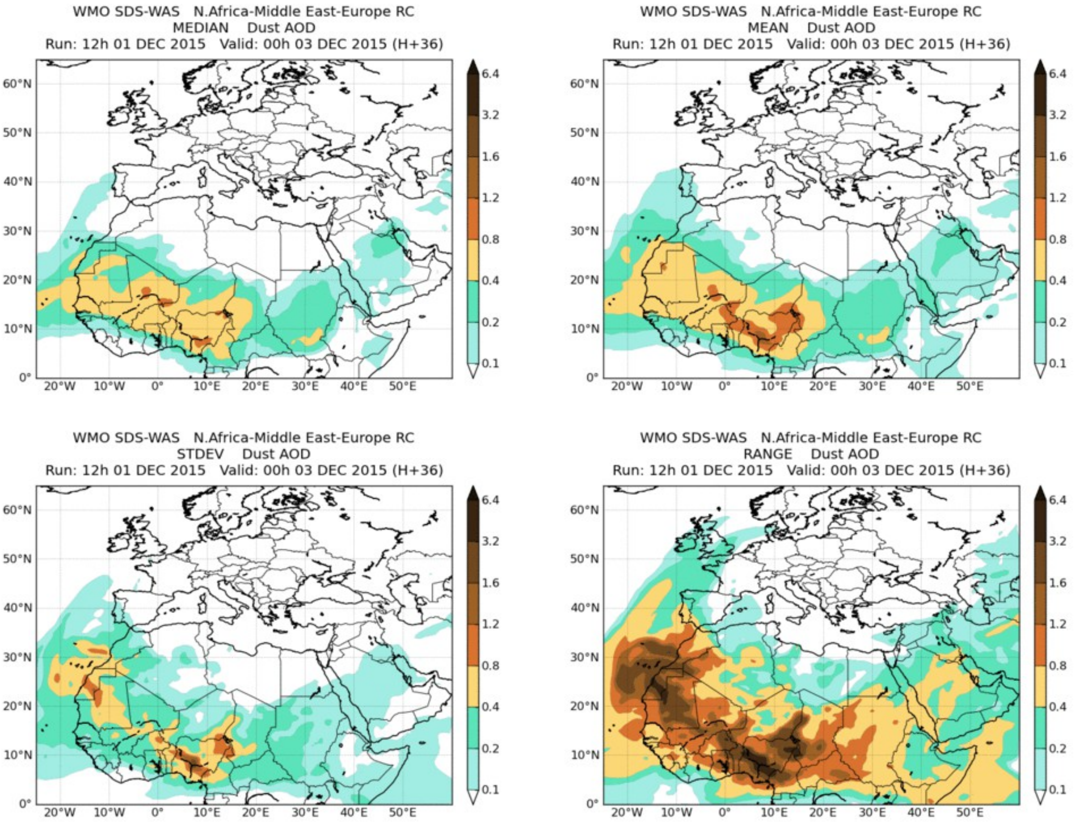

Figure 11: Multi-model products for 00 UTC 3 December 2015. Top: median and mean DOD. Bottom: Standard deviation and range of variation

An important step in forecasting is the evaluation of the results that have been generated. This process consists of the comparison of the model output with observations on different temporal and spatial scales (Benedetti et al., 2014). The first problem in identifying appropriate data for evaluation is the scarcity of dust observations. The location of the main dust sources in sparsely populated regions complicates the establishment of observing networks.

Direct-sun photometric measurements are a powerful remote-sensing tool that provides retrieval of column-integrated aerosol microphysical and optical properties. In particular, AERONET is a comprehensive set of continental and coastal sites complemented with several sparsely distributed oceanic stations that provides large and refined data sets in NRT (Holben et al. 1998; Dubovik and King 2000). Integral parameters such as aerosol optical depth (AOD) are complemented with spectral information, which permit retrieval of aerosol microphysical and composition properties (Dubovik et al. 2002). A major shortcoming of these measurements is their unavailability under cloudy skies and during night-time.

In the Regional Center, the DOD forecasts are first compared with the AOD provided by the AERONET network for 42 selected dust-prone stations located in Northern Africa, Middle East and Southern Europe. Level 1.5 of AERONET products are used for this NRT evaluation. Level 1.5 data are automatically cloud screened but don't have the final calibration applied. However, differences between Level 1.5 and Level 2 are normally quite small. Since AERONET sun photometers do not yield AOD at 550 nm, this variable is calculated from AOD at 440, 675 and 870 nm and the Ångström Exponent (AE) 440-870 using the Ångström law. Figure 12 shows the monthly plot of Santa Cruz de Tenerife, Canary Islands, in July 2015, where the different forecasts (coloured full lines) and the multi-model median (dashed black line) are compared with the AERONET AOD retrievals (yellow triangles).

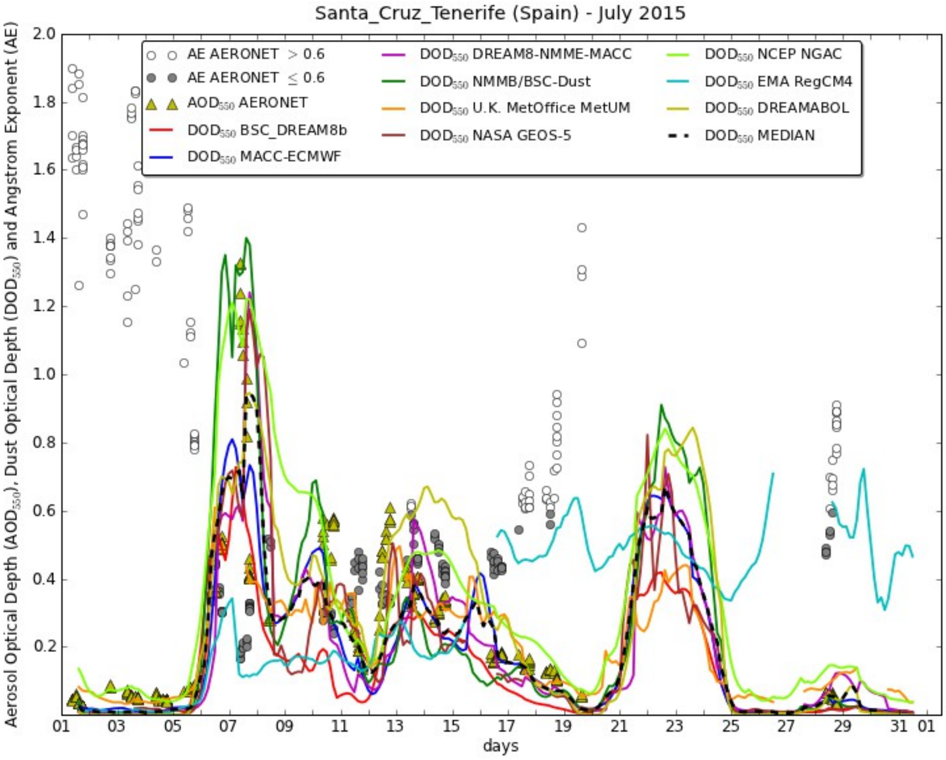

Figure 12: DOD forecast by different models (full lines) and multi-model median (dashed black line) compared with AOD (yellow triangles) retrievals from the AERONET station of Santa Cruz de Tenerife, Canary Islands, in July 2015. Black and white dots show the values of the AE, which is a first indicator of the particle size.

A system to evaluate the performance of the different models has been implemented. The system yields, on a monthly, seasonal and annual basis, evaluation scores computed from the mentioned comparison of the simulated DOD with direct-sun AOD retrievals. The evaluation system is applied to forecast values of DOD ranging from the initial day (D) at 15:00 UTC to the following day (D+1) at 12:00 UTC. It means that the lead times of the forecasts that are evaluated range from 15 to 36 hours for model runs starting at 00 UTC, but from 3 to 24 hours for model runs starting at 12 UTC. Different evaluation metrics (4) are computed in order to quantify the agreement between predictions (m_i) and observations (o_i) for individual stations, for three regions (Sahara-Sahel, Middle East and Mediterranean) and for the whole RA, as well as for different temporal scales (monthly, seasonal and annual). It should be noted that scores for individual sites can be little significant for being calculated from a small number of data. To minimize the sources of error, it is intended to restrict the comparison to situations in which mineral dust is the dominant aerosol type. Threshold discrimination is made by discarding observations with an AE 440-870 higher than 0.6 (Pérez et al., 2006). However, apart from mineral dust, other particles are always present (anthropogenic aerosol, products from biomass burning, etc.) and therefore, negative bias can be expected.

Statistic parameter	Formula	Range	Perfect score
Mean Bias Error (BE)	$BE=\frac{1}{n}\sum_{i=1}^{n}\left(m_i-o_i\right)$	−∞ to +∞	0
Root Mean Square Error (RMSE)	$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(m_i-o_i\right)^2}$	0 to +∞	0
Correlation coefficient (r)	$r=\frac{\sum_{i=1}^{n}\left(m_i-\overline{m}\right)\cdot\left(o_i-\overline{o}\right)}{\sqrt{\sum_{i=1}^{n}\left(m_i-\overline{m}\right)^2}\cdot\sqrt{\sum_{i=1}^{N}\left(o_i-\overline{o}\right)^2}}$	-1 to 1	1
Fractional Gross Error (FGE)	$FGE=\frac{2}{n}\sum_{i=1}^{n}\left\vert\frac{m_i-o_i}{m_i+o_i}\right\vert$	0 to 2	0

Table 4: Evaluation metrics used to quantify the agreement between predictions (mi) and observations (oi)

- The **mean bias error** (BE) captures the average deviations between two datasets. It has the units of the variable. Values near 0 are the best, negative values indicate underestimation and positive values indicate overestimation.

- The **root mean square error** (RMSE) combines the spread of individual errors. It is strongly dominated by the largest values, due to the squaring operation. Especially in cases where prominent outliers occur, the usefulness of RMSE is questionable and its interpretation becomes difficult.
- The **correlation coefficient** (r) indicates the extent to which patterns in the model match those in the observations.
- The **fractional gross error** (FGE) is a measure of model error that ranges between 0 and 2 and behaves symmetrically with respect to under- and over-estimation, without over-emphasizing outliers.

5 lists the annual scores 2013-2015 for the DOD forecasts of the multi-model median computed using AERONET AOD retrievals. Scores for other models, shorter periods (months, seasons) as well as smaller domains (sub-regions, single stations) are available on the Regional Center's website.

Year	Mean Bias Error	Root Mean Square Error	Correlation Coefficient	Fractional Gross Error
2013	-0.12	0.30	0.56	0.67
2014	-0.11	0.29	0.61	0.71
2015	-0.16	0.41	0.61	0.60

Table 5: Annual scores for the DOD forecasts of the multi-model median computed using AERONET AOD retrievals

The use of satellite products in forecast evaluation has the advantage of a large spatial coverage and that measurements are regular and rapidly available. The downside is that, as with AERONET, they are highly integrated over the column and over all aerosol components. The most widely used products in aerosol modelling are those based on the **MODIS** spectrometer travelling on board the Terra and Aqua satellites operated by NASA. The Regional Center first implemented an evaluation system based on a MODIS AOD product developed by the U. S. Naval Research Laboratory (NRL) and the University of North Dakota (UND). This product, specifically designed for quantitative applications including data assimilation and model validation, is generated every six hours, and time-stamped 00:00, 06:00, 12:00, and 18:00 UTC and includes MODIS measurements from +/-3 hours around the time-stamp with a horizontal resolution of 0.5 x 0.5

degree. Since the product does not provide any information for partitioning between dust and other aerosol species, the evaluation is restricted to an oceanic area, where it is known that mineral dust is by far the main source of atmospheric aerosol. The area, extending between 15º and 30º N and between 18º and 25º W, is the way of Saharan dust out to the Atlantic. This model evaluation is particularly interesting not only for the high frequency of dust events in the region, but for the key role that dust deposition, particularly intense here, plays in the cycles of iron, nitrates and other nutrients that are involved in the control of oceanic biomass productivity (Tagliabue et al., 2009). As in the evaluation with AERONET data, although mineral dust is the dominant source of aerosol in the region, other particles are likely present and, therefore, a negative bias is expected.

The DOD forecasts at 12:00 and 18:00 of D+1 are compared with the corresponding MODIS-derived values of AOD. The granules of 00:00 and 06:00 are not used, because at that times there are not MODIS retrievals over the RA. Model forecasts are bi-linearly interpolated to a 0.5 x 0.5 degree grid mesh in order to match the spatial resolution of the satellite product. Finally, models that assimilate any MODIS-derived data are not considered.

6 lists the annual scores 2014-2015 for the DOD forecasts of the NMMB/BSC-Dust model in the tropical Atlantic computed using MODIS AOD retrievals. The high occurrence of dust events in the region during 2015 (Figure 13) influences negatively on the scores for that year. Results for other models as well as shorter periods (months, seasons) are available on the Regional Center's website.

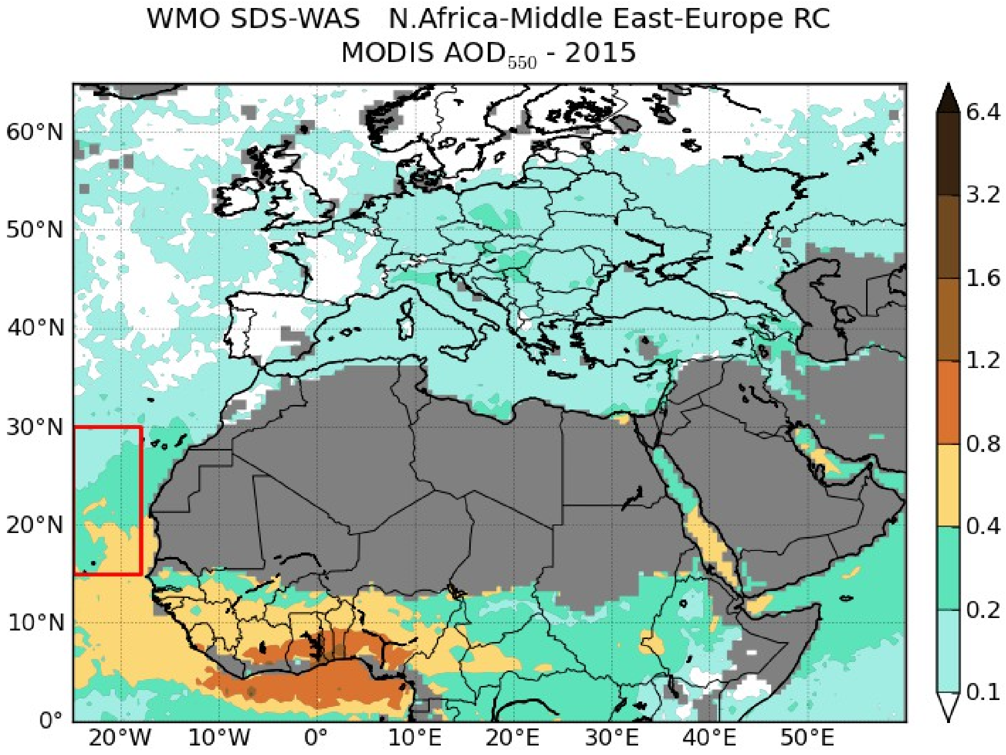

Figure 13: Average values of the MODIS AOD product of NRL and UND in 2015. Retrievals are based on the 'dark target' algorithm, which does not work over bright and highly reflective surfaces. Evaluation is restricted to the red box drawn off the cost of tropical Africa

Year	Mean Bias Error	Root Mean Square Error	Correlation Coefficient	Fractional Gross Error
2014	-0.13	0.18	0.79	1.09
2015	-0.10	0.24	0.69	0.77

Table 6: Annual scores for the DOD forecasts of the NMMB/BSC-Dust model in the tropical Atlantic computed using MODIS AOD retrievals

The difficulty of separating the aerosol signal from that of highly reflective surfaces, such as those of deserts, prevents getting information from dust source regions through satellite visible channels (see Figure 13). The MODIS **Deep Blue** aerosol retrieval algorithm uses the blue channels; in which the surface contribution is relatively low, to retrieve aerosol properties over such regions (Hsu et al., 2004; 2006).

The MODIS Deep Blue AOD retrievals are the basis for a new evaluation set-up. Retrievals are taken from the NASA’s Collection 5.1 (collection 6 since September 2014) Level-3 MODIS Atmosphere Daily Global Product with a horizontal resolution of 1 x 1 degree.

Terra and Aqua satellites turn in a sun-synchronous orbit. Their overpass time is around 12:00 local time in its ascending (daytime) mode. Therefore, the forecasts of dust optical depth (DOD) at 12:00 of D+1 are compared with the corresponding MODIS-derived values of AOD. The maximum lag between observation and prediction is of 3-4 hours. It is intended to restrict the comparison to situations in which mineral dust is the dominant aerosol type. Threshold discrimination is made by discarding observations with a MODIS-retrieved AE 412-490 higher than 1.0. However, besides dust, there are other particles and, therefore, a negative bias can be expected in the scores.

Model forecasts are bi-linearly interpolated to a 1 x 1 degree grid mesh in order to match the spatial resolution of the MODIS Deep Blue retrievals. As with the previously described set-up, only those models that do not assimilate any MODIS product are considered.

This model evaluation is particularly interesting because Deep Blue retrievals are one of the few sources of information on the dust content over deserts (see Figure 14). 7 shows the annual scores 2014-2015 for the DOD forecasts of the NMMB/BSC-Dust model computed using MODIS Deep Blue AOD retrievals. Results for other models as well as shorter periods (months, seasons) are available on the Regional Center's website.

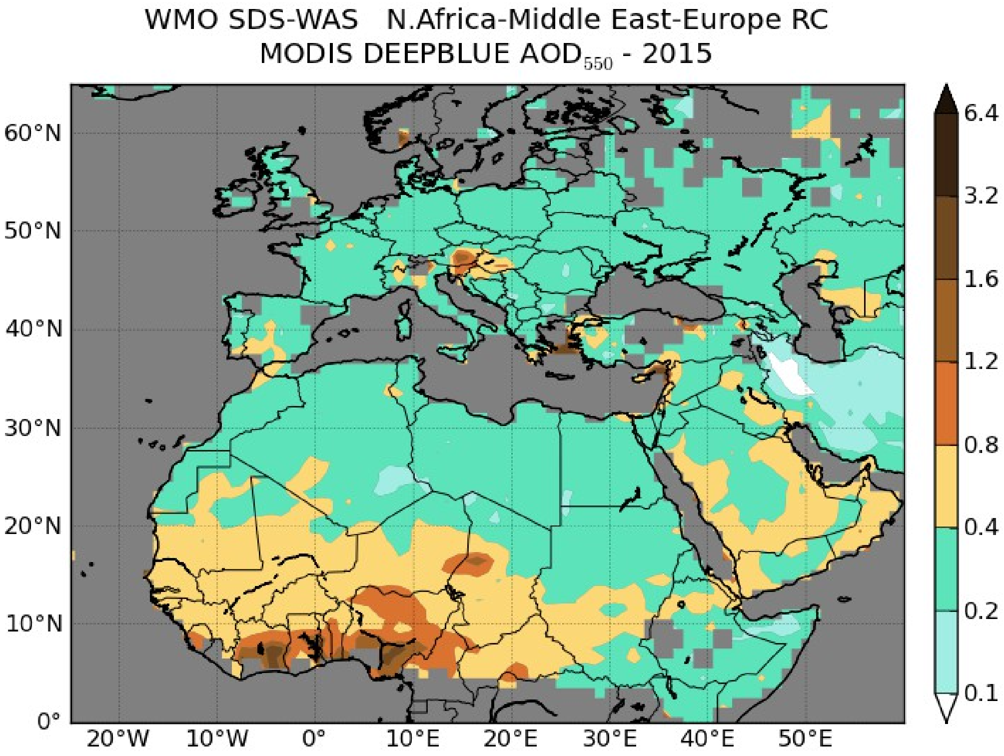

Figure 14: Average values of the MODIS Deep Blue AOD product in 2015. Retrievals with an AE 412-490 higher than 1.0 have not been considered

Year	Mean Bias Error	Root Mean Square Error	Correlation Coefficient	Fractional Gross Error
2014	-0.13	0.31	0.44	0.95
2015	-0.09	0.36	0.60	0.84

Table 7: Annual scores for the DOD forecasts of the NMMB/BSC-Dust model computed using MODIS Deep Blue AOD retrievals

In addition to the systematic evaluation of the columnar dust content, there have been attempts aimed at implementing an evaluation system for dust surface concentration, which is a relevant variable for many application fields. The first problem is the scarcity of suitable routine observations. Air quality monitoring networks perform systematic measurements with high spatial density in developed countries, but very sparse, discontinuous and rarely NRT available close of the main dust sources. As with the satellites, air quality measurements integrate the contribution of all types of atmospheric aerosol. Furthermore, observational values are usually limited to the concentration of particulate matter with an aerodynamic diameter less than 10 µm (PM10), which does not always encompass the full size range of dust particles suspended in the atmosphere. Finally, it is important to consider the selection of stations, since many of them are located in cities, industrial parks or roads, where local human activity is the main source of particles, and others are located next to the sea and so affected by marine aerosol. In both cases, the contribution of dust to the measured quantities is masked by other particles.

In Northern Africa, the only reliable information of aerosol surface concentration close to dust sources is that provided by three monitoring stations deployed in the Sahel in the frame of the **African Monsoon Multidisciplinary Analysis** (AMMA) project (Marticorena et al., 2010). Tapered Element Oscillating Micro-balance (TEOM) monitors continuously record PM10 in M'Bour, Senegal; Cinzana, Mali and Banizoumbou, Niger. A first study (Terradellas et al, 2015b) compares the AMMA dataset with 24-hour forecasts delivered by seven dust prediction models for 2013. Although mineral dust is the dominant aerosol type in the region, incursions of the monsoon flow eventually allow transport of biomass burning aerosol from southern sources. Thus, following Marticorena et al. (2010), a wind-based filter is introduced to remove these cases from the model evaluation. The study concludes that forecasts reproduce the annual variation observed in the PM10 records, although models tend to over-estimate the observation. The performance skill of the different models is summarized in the Taylor diagrams presented in Figure 15.

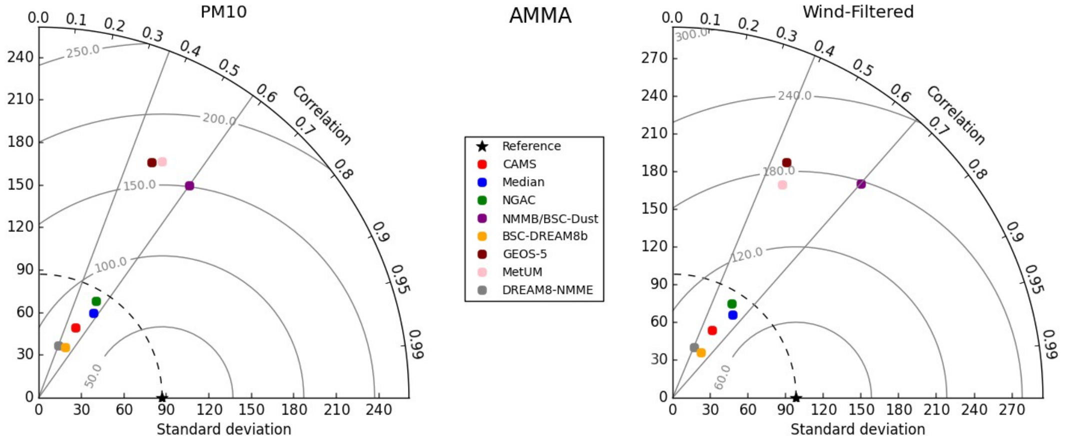

Figure 15: Taylor diagrams describing the performance skill of the different models and multi-model median in the Sahel in 2013. The models are compared with raw PM10 data (left) and filtered data (right)

A second study has been conducted using PM10 records from the **Air Quality Control and Monitoring Network** in the Canary Islands, Spain, for the period 2013-2014 (García-Castrillo et al., 2016). The Canary Islands are located on the western outflow of the Saharan desert and, therefore, are suitably located to suffer frequent Saharan dust outbreaks. The presence of relatively high levels of anthropic pollutants and marine aerosol forces the filtering of PM10 data. Two different methods have been tested to quantify the presence of mineral dust in the overall PM10 burden. The first method (Escudero et al., 2007) is based on the subtraction of a daily regional background level computed from the 40th percentile of a 30-day moving average. The second method consists of the use of PM10-PM2.5 values, that is, eliminating the fine particles from the measured datasets.

Also, work has been done to find an empirical equation relating visibility and dust surface concentration. Although visibility reduction does not only depend on mass concentration, but also on particle size, density and chemical composition (e. g. Charlson, 1969), an empirical relationship between these two variables could be very useful for model evaluation. Camino et al. (2015) derived an equation from observations recorded at the Izaña Atmospheric Observatory during Saharan dust outbreaks between 2003 and 2010 and then validated it with the AMMA PM10 measurements in the Sahel. However, one must be aware that such relationship has been derived for North-western African sources and can not be used universally.

3.4. Cooperation with the Monitoring Composition and Climate project

The **Monitoring Atmospheric Composition and Climate** (MACC) project, and its successors MACC-II and MACC-III, aim at establishing the core global and regional atmospheric environmental service delivered as a component of the European Earth observation programmes **Global Monitoring for Environment and Security** (GEMS) and **Copernicus**. MACC services covered, among other fields, air quality and atmospheric composition.

The MACC daily aerosol analysis and forecast includes atmospheric reactive gases, greenhouse gases and aerosol, and is based on the Integrated Forecasting System of the European Centre for Medium-Range Weather Forecasts (ECMWF). The global component of the MACC service has a dedicated validation activity to document the quality of the atmospheric composition products (Eskes et al., 2015).

The expertise of the SDS-WAS Regional Center on dust model evaluation enabled it to become one of the key contributors to this MACC component. In particular, Cuevas et al. (2015b) evaluated and analysed a 2-year reanalysis with an improved dust parametrization scheme implemented specifically for this study.

3.5. Sand and Dust Storm Africa

In June 2013, a new AERONET station has been set in Tunis-Carthage, Tunisia, in the framework of the **SDS-Africa project**, which has been financed by the Spanish Agency for International Development Cooperation (AECID) through a WMO trust fund and implemented by the AEMET's Izaña Atmospheric Research Center (IARC). This station completes the IARC network in Northern Africa, which includes sites in the Canary Islands (Spain), Morocco, Algeria, Tunisia and Egypt. The new station is jointly managed by the Tunisian National Meteorological Institute and AEMET.

The main goals of the SDS-Africa project are the characterization of the Saharan air ayer, the early warning of dust storms, the verification of satellite-based products, and the validation of regional and global dust models.

Every 12-15 months, the sensor of each sun-photometer of the network is replaced with a calibrated one by the **AERONET-Europe Calibration Service**. Also, great attention has been paid to capacity building activities. Sensor replacement operations are harnessed to provide training to field operators. The capacity building missions conducted in the period 2013-2015 are summarized in 8 (Cuevas et al., 2015a)

Place	Date
Ouarzazate, Morocco	17-21 Mar 2013
Tunis, Tunisia	10-14 Jun 2013
Izaña, Spain	24-28 Jun 2013
Algiers, Algeria	10-12 Dec 2013
Izaña, Spain	22-26 Sep 2014
Izaña, Spain	17-21 Nov 2014
Izaña, Spain	1-5 Dec 2014
Izaña, Spain	19-23 Oct 2015
Izaña, Spain	30 Nov – 4 Dec 2015

Table 8: Training courses targeted to field operators of SDS-Africa AERONET stations

3.6. Coordination of collaborative projects

The Regional Center coordinates several collaborative research projects, in which different organizations are taking part. These projects are aimed to study in detail particular cases and/or to better understand the features of the atmospheric dust process. The main conclusions of these studies are published as reports or scientific articles

The first research project (Huneeus et al., 2016) analysed the performance of different models during a dust outbreak over Europe (Figure 16). Four state-of-the-art dust forecast models were examined to assess their performance to predict up to 72 hours ahead an intense Saharan dust outbreak over Western Europe up to Scandinavia between 5th and 11th April 2011. The capacity of the models to predict the evolution of the dust cloud was assessed by comparing their results with AOD from AERONET and MODIS, as well as with dust surface concentration from air-quality monitoring stations. In addition, extinction vertical profiles from CALIOP were used to examine the predicted vertical dust distribution of each model. To identify possible reasons for the different model performance, the simulated wind fields were compared with 10-m winds observed at meteorological stations and vertical wind profiles from two radio sounding stations located in the source region.

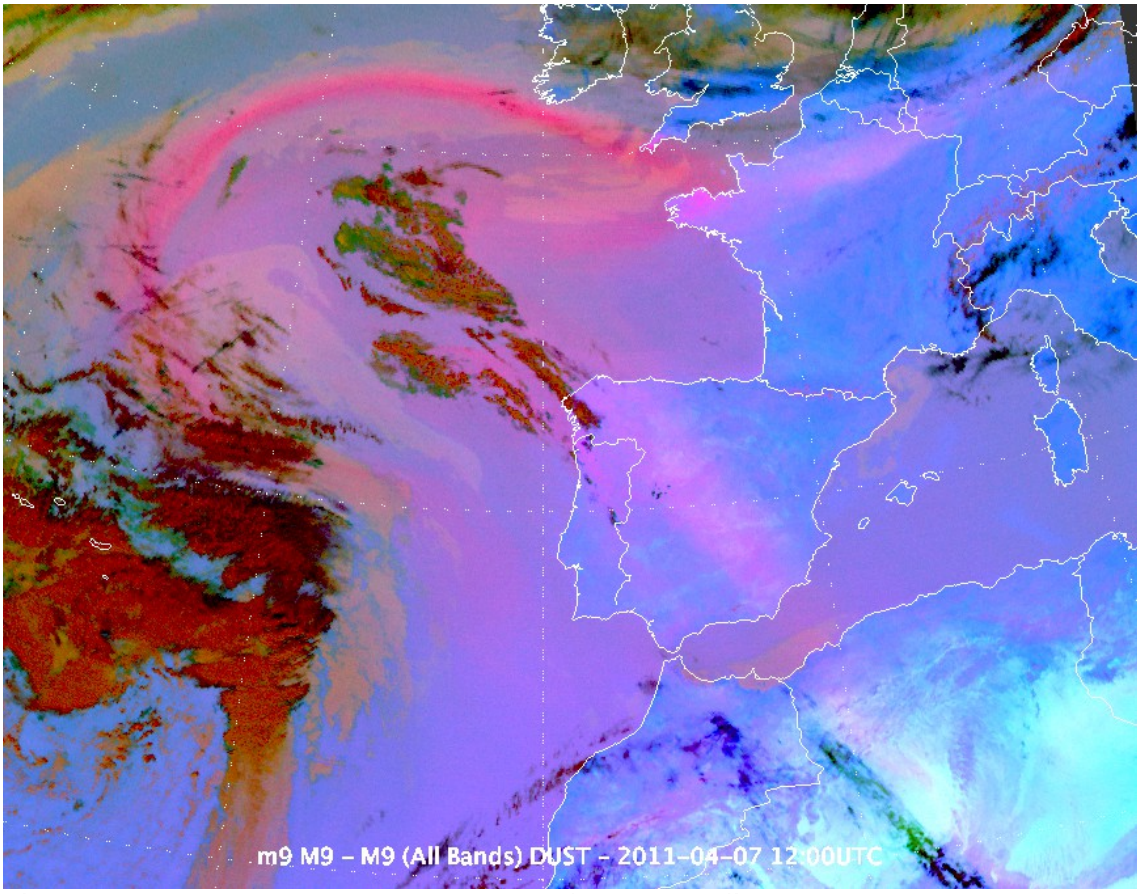

Figure 16: METEOSAT-9 Dust RGB composite on 7 April 2011 12:00 UTC

A second project (Binietoglou et al., 2015) compared model forecasts with lidar products over two years (Figure 17). Dust concentration forecast by different numerical models was compared with retrievals from lidar co-located with sun photometers using the Lidar/Radiometer Inversion Code (LIRIC), which is an algorithm that permits the retrieval of the volume concentration profiles of various atmospheric aerosol components, based on the synergy of a multi-wavelength lidar and an AERONET sun photometer. LIRIC separates the atmospheric aerosol into two types: fine mode (smoke, urban pollution) and coarse mode (desert or volcanic dust, marine aerosol); if lidar depolarization measurements are also available, the coarse mode is further divided into two sub-modes: coarse/spherical (marine) and coarse/non-spherical (mineral dust). The LIRIC algorithm calculates the micro-physical properties and the volume concentration profiles of these components by optimizing the fit of the modelled profiles and the lidar/photometer measurements. Thus, the dust components of the measured aerosol can be separated, making the comparison with dust model simulations straight-forward.

Figure 17: Map of ACTRIS/EARLINET remote sensing stations that provided data to test the LIRIC algorithm

The next project is the ongoing study of a haboob in Tehran, Iran (Figure 18). The subject is the small-scale extreme dust storm occurred in Tehran on 2nd June 2014, at 17:30 local time, lasting less than 2 hours according to public evidence. Based on public news, the blowing wind reached 110 km/h and the dust storm caused several deaths, reduction of visibility to several tenths of meters, and disturbance of the street traffic. According to public information and limited observations currently available, it has been hypothesized that the dust storm passing over Tehran was generated by a small-scale atmospheric circulation such as a squall line or a convective down-draft. This project is a response to the discussion of the SDS-WAS RSG during its regular meeting held in Italy on June 4th, 2014, on the Tehran event. The RSG noted that eight dust models, routinely operated within the SDS-WAS regional node, predicted increase of dust concentration in a wide area of northern Iran, but none of them were able to predict the dust storm over Tehran due to the fact that their coarse resolution could not resolve the small scales of the phenomenon.

Figure 18: Image of the haboob in Tehran on 2 June 2014: the dust wall about to envelop the telecommunication tower

3.7. Capacity building

Following the efforts made in previous years, the Regional Center has organized new training events to promote the use of observational and forecast products distributed in the framework of the WMO SDS-WAS. The events organized by the Center in the period 2013-2015 have been:

- 3rd Training Course on WMO SDS-WAS products (satellite and ground observation of atmospheric dust).
- 4th Training Course on WMO SDS-WAS products (satellite and ground observation of atmospheric dust)

The **3rd Training Course on WMO SDS-WAS products** (Figure 19) was held in Muscat, Oman, on 8-12 December 2013. It was organized by the Regional Center in cooperation with WMO, EUMETSAT, the Directorate General of Meteorology and Air Navigation of Oman (DGMAN) and the Sultan Qaboos University.

Figure 19: Participants in the 3rd Training Course on WMO SDS-WAS products held in Muscat, Oman

42 participants from 11 countries (Bahrain, Egypt, Iceland, Iran, Iraq, Nigeria, Oman, Qatar, Saudi Arabia, Sudan and U. A. E.) attended the course. The lectures were delivered by Zeinab Saleh (Egyptian Meteorological Authority), Khalid Khamis Al-Jahwari (DGMAN), Sultan Al-Yahyai (DGMAN), José María Baldasano (BSC), Francesco Benincasa (BSC), Emilio Cuevas (AEMET), Jose Prieto (EUMETSAT), Hans-Peter Rösli (EUMETSAT), Kerstin Schepanski (Leibniz Institute for Tropospheric Research) and Enric Terradellas (AEMET). The event was complemented with the '**McIDAS-V Tutorial with focus on atmospheric dust cases**', conducted on 15-16 December 2013.

The 4th Training Course on WMO SDS-WAS products (Figure 20) was held in Casablanca, Morocco, on 17-20 November 2014. It was financed by AEMET, EUMETSAT and the National Meteorology Direction (DMN) of Morocco.

Figure 20: Participants in the 4th Training Course on WMO SDS-WAS products held in Casablanca, Morocco

Participants from 9 countries (Algeria, Egypt, The Gambia, Iran, Iraq, Morocco, Niger, Togo and U. A. E.) and from ACMAD attended the course. The lectures were delivered by Ashraf Zakey Saleh (Egyptian Meteorological Authority), Enric Terradellas and Sergio Rodríguez (AEMET), Sara Basart and Francesco Benincasa (BSC), Alexander Baklanov (WMO), José Prieto and Jochen Kerkmann (EUMETSAT) and Tahar Saouri (DMN).

The Regional Center has also contributed to training events organized by other institutions, the most remarkable being:

The **Training Course on the Use of Satellite Products for Agrometeorological Applications** was organized by WMO and EUMETSAT with the support of the Ghana Meteorological Agency**.** It was conducted in Accra, Ghana, between 10th and 14th June 2013, in the framework of the Metagri-Operational project. The main objective of this project is the provision of convenient weather and climate information for the benefit of food producers in the Western Africa rural world. A specific objective is to build capacity of NMHSs to provide more an and better agrometeorological products and services based on the use of satellite data. The event was attended by experts from Cape Verde, Ethiopia, The Gambia, Ghana, Kenya, Liberia, Nigeria, Tanzania and Uganda.

The **Workshop on Meteorology, Sand and Dust Storm, Combating Desertification and Erosion** was held in Istanbul, Turkey, 28-31 October 2013. it was jointly organized by three Turkish institutions: the General Directorate of Combating Desertification and Erosion, the Turkish State Meteorological Service and the General Directorate of Forestry (Figure 21). The event was attended by technicians from Northern Africa, Middle East and Europe. In particular, experts on meteorology from Iran, Jordan, Lebanon, Morocco, Saudi Arabia, Serbia, Spain, Sudan, Tunisia, Turkey U. A. E. and Yemen worked together with experts in forestry, desertification and erosion.

Figure 21: Participants of the Workshop on Meteorology, Sand and Dust Storm, Combating Desertification and Erosion

The third edition of the **Training Course on the Use of Satellite Products for Agrometeorological Applications**, again organized by the WMO and EUMETSAT, was aimed to address specific needs of the agrometeorological community of Western Africa. It was conducted in French in Ouagadougou, Burkina Faso, 5-9 May 2014 and included several presentations linked to the Virtual Lab concept, open online to any interested participant in the world. Established by

WMO and the Coordination Group for Meteorological Satellites (CGMS), the **Virtual Laboratory for Training and Education in Satellite Meteorology** (Virtual Lab) is a global network of specialized training centres and meteorological satellite operators working together to improve the utilisation of data and products from meteorological and environmental satellites.

The fourth edition of the **Training Course on the Use of Satellite Products for Agrometeorological Applications** was held in Addis Ababa, Ethiopia, 23-27 March 2015 (Figure 22). It was organized by WMO, EUMETSAT and the Ethiopian National Meteorological Agency, as local organizer. Also Food and Agriculture Organization (FAO), European Commission's Joint Research Centre (JRC), Royal Meteorological Institute of Belgium, University of Reading and AEMET contributed to the event. Meteorologists from Burundi, Ethiopia, The Gambia, Kenya, Malawi, Nigeria, Rwanda, South Sudan, Tanzania, Uganda, Zambia and Zimbabwe attended the course.

Figure 22: Ethipian participants in the fourth edition of the Training Course on the Use of Satellite Products for Agrometeorological Applications

3.8. Participation in outstanding international meetings

The **Technical Meeting on UNEP Regional Programme to Combat Sand and Dust Storms** was held in Abu Dhabi, 6-7 May 2013 under the patronage of H.E the Minister of Environment and Water of the United Arab Emirates (UAE). It was hosted by the Ministry of Environment and Water and the UAE National Centre for Meteorology and Seismology (NCMS). The meeting was attended by about 50 representatives from governments of the Region, United Nations, League of Arab States, Gulf Cooperation Council, and other regional and international organisations. The aim of the meeting was to seek the views and inputs of the participating countries to the three pillars of a proposed Regional Sand and Dust Programme (regional cooperation framework, regional trust fund and technical programme).

After presentation of a regional assessment on climatological trends of sand and dust storms delivered by Emilio Cuevas (AEMET), discussion focused on the need for a monitoring network and an early warning system, as well as on priority actions at the regional and national levels to effectively combat sand and dust storms. Finally, a road-map towards programme development, coordination and financing was agreed.

Sand and Dust Storm: Forecast Services (Figure 23) was a side-event of the **17th Session of the World Meteorological Congress** that was held on 8 June 2015 at the Geneva International Conference Centre, Switzerland. The event, chaired by Enric Terradellas (AEMET) was intended to publicize and promote the operational forecast products delivered by the **Barcelona Dust Forecast Center**, described in Section 4. Presentations were delivered by Alexander Baklanov and Abdoulaye Harou (WMO), Enric Terradellas (AEMET) and Sara Basart (BSC).

Figure 23: Sand and Dust Storm: Forecast Services

The **WHO Consultation meeting on air quality and health in the Eastern Mediterranean Region** took place from 10 to 11 December 2014 in Amman, Jordan. It supported framing of national policies to protect health from air pollution impacts, advocated for health-based air pollution control policy and management interventions by other relevant sectors, and promoted monitoring and surveillance of the health impacts of air pollution. Enric Terradellas (AEMET) reported on the health impact of airborne dust with special focus on the region and presented the available monitoring and forecast products. An outcome of the meeting was the need to convene a workshop with participation of experts in health, air quality and meteorology to discuss specifically about these impacts.

The edge of crisis: Sand and Dust Storms was a side event held on 15th October 2015 in Ankara, Turkey, during the Twelfth Session of the **Conference of the Parties** (COP12) of the **United Nations Convention to Combat Desertification** (UNCCD). It was organized by UNEP, UNCCD, WMO, China State Forestry Administration (CSFA) and Korea Forest Service and included presentations by Monique Barbut and Louise Baker (UNCCD), Gemma Shepherd (UNEP), Deon Terblanche (WMO), Enric Terradellas (AEMET), Cihan Dundar (Turkish State Meteorological Service, TSMS) and Lu Qi (CSFA). The event was aimed to identify actions that UNCCD and its partners must take to reduce the frequency of the phenomenon and to mitigate its adverse effects on air quality, human health, and land and marine ecosystems. **Deon Terblanche**, Director of the WMO Atmospheric Research and Environment Department, presented the WMO SDS-WAS, which could become part of a wider United Nations system to better manage this phenomenon and its impacts. He stated that over the past 10 years, SDS-WAS fostered global research and cooperation on sand and dust storm related matters in order to improve forecasts and warnings. He added that WMO’s activities focus mainly on the understanding of sand and dust storm processes, its modelling and the prediction of such events to improve early warning services. **Enric Terradellas**, Technical Director of the Barcelona Dust Forecast Center (BDFC) that is described in Section 4, discussed about the transition from R&D to operational dust forecasts and presented the BDFC and its activities. In the conclusion, It was stressed the need for a global assessment on the extent, frequency and impact of sand and dust storms, as well as future trends associated to climate and land use change. Both WMO and UNEP agreed to lead the study, which would also involve the BDFC.

3.9. 1st Africa / Middle East Expert Meeting and Workshop on the Health Impact of Airborne Dust

Following the recommendation of the WHO Consultation meeting on air quality and health in the Eastern Mediterranean Region, WHO, WMO, UNEP, EUMETSAT and AEMET sponsored the **1st Africa/Middle East Expert Meeting and Workshop on the Health Impact of Airborne Dust** held in Amman, Jordan, from 2 to 5 November 2015, co-chaired by Abdul-Majeid Haddad (UNEP), Mazen Malkawi (WHO) and Enric Terradellas (AEMET).

The main objective was to assess the state of knowledge and to encourage countries' actions with regard to impacts of airborne dust on public health in the Middle East – Northern Africa region. The Expert Meeting and Workshop promoted active communication among dust-related service providers, NMHSs and relevant national and international environment, air-quality and public health agencies.

The opening ceremony (Figure 24) was presided by the Jordan Minister of Environment, H. E. Dr. **Taher Shakhshir**, and featured speeches from representatives of the supporting institutions. Different sessions were attended by 59 experts from Algeria, Bahrain, Burkina Faso, Egypt, Iraq, Jordan, Kuwait, Lebanon, Mauritania, Morocco, Pakistan, Palestine, Saudi Arabia, Spain, Sweden, Tunisia, U. A. E., U. S. A. and Yemen, apart of representatives of the sponsoring international organizations.

Figure 24: Opening of the 1st Africa / Middle Eastr Expert Meeting and Workshop on the Health Impact of Airborne Dust

The main conclusions can be summarized as follows:

a) Health:

- Plenty of evidence on the health impact of particulate matter (including airborne dust) exists globally and can be utilized in the region in the absence of local evidences.
- More resources (research and exchange of information) are needed to fill in the shortage of local evidence.
- Efficiency of existing interventions to minimize exposure to airborne dust (masks, staying indoors, …) is not fully known.
- Lack of preparedness to respond to episodes of air pollution still persists in the region.

b) Meteorology:

- Global sand and dust monitoring, modelling and forecasting capacities exist. However, the present capabilities for capturing local and regional sand and dust episodes must be further improved.
- National capacities for local monitoring, modelling and forecasting are still limited.
- Data sharing at country and inter-country levels needs to be strengthen.
- There is a lack of research in the area.

c) Air quality:

- There are reasonable capabilities for air quality monitoring in some countries of the region. However, few initiatives on chemical and physical speciation and source apportionment do exist so far.
- Reliability of data is an issue, as cross-calibration is generally not available.
- Research activities are facing difficulties.

4. Barcelona Dust Forecast Center: From R&D to operational services. Activity 2013-2015

In May 2013, in view of the demand of many national meteorological services and the good results obtained by the SDS-WAS, which prove the feasibility and the need to begin developing operational services beyond the scope of R&D, the 65th Session of the WMO Executive Council designated the consortium formed by AEMET and the BSC to create in Barcelona the first Regional Specialized Meteorological Center with activity specialization on Atmospheric Sand and Dust Forecast (RSMC-ASDF). The Center began operating in February 2014 with the name of **Barcelona Dust Forecast Center**. It generates and distributes dust predictions for Northern Africa (north of equator), Middle East and Europe on an operational way.

Figure 25: Public presentation of the Barcelona Dust Forecast Center

The Barcelona Dust Forecast Center was publicly presented on 10 June at the AEMET headquarters in Madrid, Spain. "This initiative meets a clear need. In many regions and countries of the world, sand and dust storms constitute a significant hazard" said WMO Secretary-General **Michel Jarraud** in a video message to the inaugural event. “The implications of atmospheric sand and dust for human health are serious. It is estimated that two billion people living in arid zones are directly affected by sand and dust. The population living far away from the source region is exposed as well to a lesser extent. Health impacts include respiratory and cardiovascular illnesses, eye infections and also meningitis and valley fever. Other impacts include negative effects on ground transport, aviation, agriculture and

Figure 26: Video message of the WMO Secretary-General Michel Jarraud to the inaugural event

visibility", he continued.

The presentation event was also attended by Ivan Cacic, President of WMO Regional Association VI (Europe), who welcomed this new centre and thanked the proactive role of Spain within WMO community, highlighting the interregional role Spain plays in activities like this, affecting WMO Regional Associations I (Africa), II (Asia) and VI (Europe) or its leadership in other initiatives for the Greater Mediterranean Region such as Mediterranean Climate Outlook Forum (MedCOF) or MEditerranean climate DAta REscue (MEDARE).

The event counted with the technical presentations of eminent scientists in the field: Emilio Cuevas (AEMET), Alexander Baklanov (WMO) and José María Baldasano (BSC). These presentations highlighted the impact of dust on weather and climate and that 50 per cent of the total atmospheric dust mass originates from soils that are disturbed by cultivation, erosion, frequent shifts in vegetation due to drought and rains and especially deforestation. Finally, they also emphasized that the new BDFC builds on the R&D success of the WMO SDS-WAS and, specifically, its Regional Center for Northern Africa, Middle East and Europe.

4.1. Operational products

The Barcelona Dust forecast Center prepares regional forecast fields based on NMMB/BSC-Dust model simulations continuously throughout the year on a daily basis. NMMB/BSC-Dust consists of a numerical weather prediction model incorporating on-line parametrizations of all the major phases of the atmospheric dust cycle. A detailed description is provided in the next Section.

The BDFC generates forecasts of the following set of variables:

- **Dust load** (kg.m^{-2}).
- **Dust surface concentration** (µg.m^{-3}).
- **Dust optical depth at 550 nm** (-).
- **3-hour accumulated dry and wet deposition** (kg.m^{-2}).
- **Dust surface extinction** (Mm^{-1}).

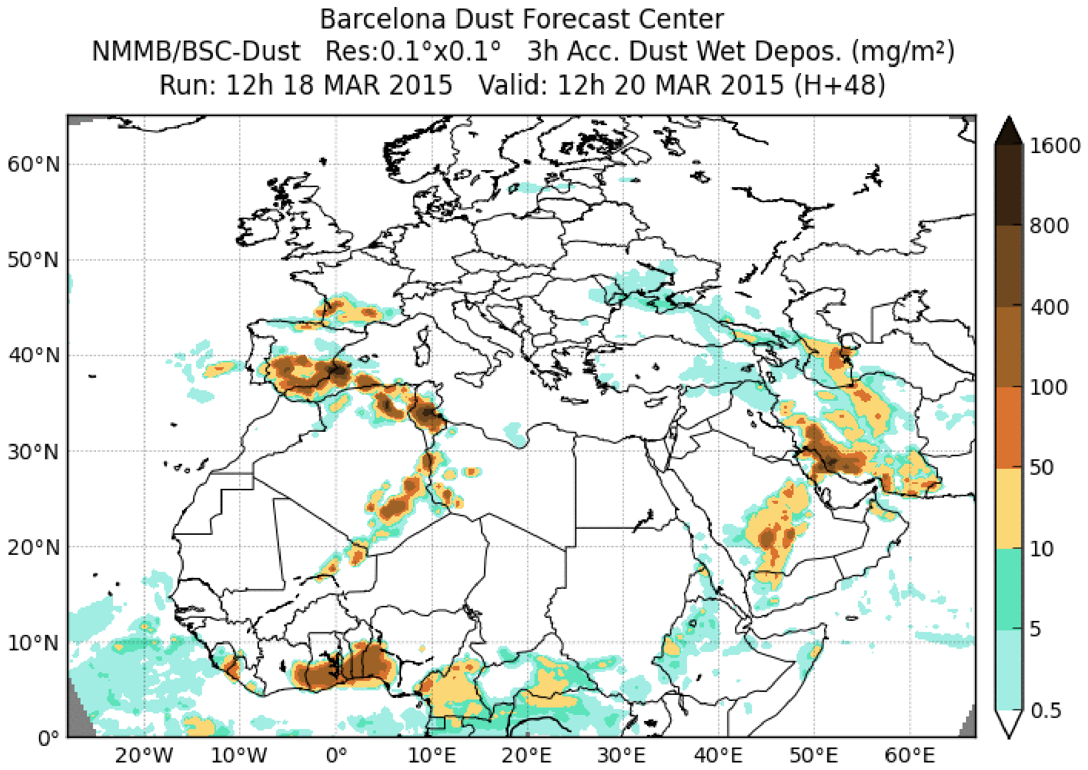

Figure 27: 48-h forecast of dust wet deposition valid for 20 Mar 2015 12:00

Forecasts cover the period from the starting forecast time (12 UTC) up to a forecast time of 72 hours, with an output frequency of 3 hours. They cover Northern Africa (north of equator), Middle East and most of Europe with a horizontal resolution of 0.1 x 0.1 degree. Products are distributed 12 hours after the starting forecast time, that is, at 0 UTC of the following day.

The model outputs are stored, both in NetCDF and in WMO FM 92 GRIB Edition 2 formats. For GRIB files, version 13.0.0 of the code tables is used:

- Templates v. 13.0.0
- Code and flag tables v. 13.0.0
- Local tables v. 1.0.0 (9). These tables have been built by the BDFC to complement the WMO Master Tables in order to enable encoding/decoding dust-related products.

Number	Parameter	Units
248	Dust surface extinction at 550 nm	Mm^{-1}
249	Dust load	$g.m^{-2}$
250	3-hour accumulated dust dry deposition	$mg.m^{-2}$
251	3-hour accumulated dust wet deposition	$mg.m^{-2}$
252	Dust surface concentration	$\mu g.m^{-3}$
253	Dust optical depth at 550 nm	-

Table 9: Local tables v. 1.0.0 include the Code table 4.2: parameter number by product discipline and parameter category for Product discipline 0 (meteorological products) and parameter category 13 (aerosol)

4.2. NMMB/BSC-Dust model

The **NMMB/BSC-Dust** (Pérez et al., 2011; Haustein et al., 2012) is an online multi-scale atmospheric dust model designed and developed at the BSC in collaboration with three North-American institutions: the NOAA's National Centers for Environmental Prediction (NCEP), the NASA's Goddard Institute for Space Studies and the International Research Institute for Climate and Society (IRI). The model is fully embedded into the **Non-hydrostatic Multi-scale Model on the B-grid** (NMMB) developed at NCEP (Janjic and Black, 2005; Janjic et al., 2011) and is intended to provide short to medium-range dust forecasts for both regional and global domains.

The NMMB/BSC-Dust model solves the mass balance equation for dust taking into account the following processes:

- Dust generation and uplift by surface wind and turbulence.
- Horizontal and vertical advection (Janjic et al., 2009).
- Horizontal diffusion and vertical transport by turbulence and convection (Janjic et al., 2009).
- Dry deposition and gravitational settling (Zhang et al., 2001).
- Wet removal including in-cloud and below-cloud scavenging from convective and stratiform clouds (Betts, 1986; Betts and Miller, 1986; Janjic, 1994; Ferrier et al., 2002).

The physically-based dust emission scheme explicitly takes into account saltation and sandblasting processes (White, 1979;

Marticorena and Bergametti, 1995; Marticorena et al., 1997) and assumes a viscous sub-layer between the smooth desert surface and the lowest model layer (Janjic, 1994; Nickovic et al., 2001).

The soil size distribution is specified through the textures of the FAO soil map. Four soil populations are used in the model, distinguishing between fine-medium and coarse sand, according to the criteria detailed in Tegen et al. (2002).

The size-integrated dust vertical flux is distributed according to the 3 source modes of D'Almeida (1987) and then over each of the 8 transport bins with intervals taken from Tegen and Lacis (1996) and Pérez et al. (2006). For the source function, the model uses the topographic preferential source approach after Ginoux et al. (2001) and the National Environmental Satellite Data, and Information Service (NESDIS) vegetation fraction climatology (Ignatov and Gutman, 1998). Inhibition of dust production by soil moisture is included following Fécan et al. (1999).

The effects of aerosol, and mineral dust in particular, on radiation are computed interactively by means of the Rapid Radiative Transfer Model (RRTM) (Mlawer et al., 1997).

The NMMB/BSC-Dust model has been evaluated at regional and global scales (Pérez et al., 2011; Haustein et al., 2012). At the global scale, the model lies within the top range of **Aerosol Comparisons** (AeroCom) dust models in terms of performance statistics for surface concentration, deposition and AOD (Huneeus et al., 2010). At regional scale, the model reproduces significantly well the daily variability and the seasonal spatial distribution of the DOD over Northern Africa, Middle East and Europe.

4.3. Forecast evaluation

Following the procedure developed by the SDS-WAS Regional Center that has been described in Section 3.3, the operational forecasts of DOD are compared with the AOD retrievals provided by the AERONET network for the 42 dust-prone stations listed in 10.

Site name	**Country**	**Longitude**	**Latitude**	**Region**
Avignon	France	4.88ºE	43.93ºN	Mediterranean
Banizoumbou	Niger	2.66ºE	13.54ºN	Sahel/Sahara
Barcelona	Spain	2.12ºE	41.39ºN	Mediterranean
Cabo_da_Roca	Portugal	9.50ºW	38.78ºN	Mediterranean
Caceres	Spain	6.34ºW	39.48ºN	Mediterranean
Cairo_EMA_2	Egypt	31.29ºE	30.08ºN	Mediterranean
Avignon	France	4.88ºE	43.93ºN	Mediterranean
Capo_Verde	Cape Verde	22.93ºW	16.73ºN	Sahel/Sahara
CUT-TEPAK	Cyprus	33.04ºE	34.67ºN	Mediterranean
Dakar	Sénégal	16.96ºW	14.39ºN	Sahel/Sahara
Eilat	Israel	34.92ºE	29.50ºN	Mediterranean
Ersa	France	9.36ºE	43.00ºN	Mediterranean
ETNA	Italy	15.02ºE	37.61ºN	Mediterranean
Evora	Portugal	7.91ºW	38.57ºN	Mediterranean
FORTH_CRETE	Greece	25.28ºE	35.33ºN	Mediterranean
Granada	Spain	3.60ºW	37.16ºN	Mediterranean
IASBS	Iran	48.51ºE	36.70ºN	Middle East
IER_Cinzana	Mali	5.93ºW	13.28ºN	Sahel/Sahara
Ilorin	Nigeria	4.34 ºE	8.32ºN	Sahel/Sahara
IMAA_Potenza	Italy	15.72ºE	40.60ºN	Mediterranean
IMS-METU-ERDEMLI	Turkey	34.26ºE	36.56ºN	Mediterranean
KAUST_Campus	Saudi Arabia	39.10 ºE	22.30 ºN	Middle East
Kuwait University	Kuwait	47.97 ºE	29.33 ºN	Middle East
Lampedusa	Italy	12.63ºE	35.52ºN	Mediterranean
Lecce_University	Italy	18.11ºE	40.33ºN	Mediterranean
Oujda	Morocco	1.90ºW	34.65ºN	Mediterranean
Ouarzazate	Morocco	6.91ºW	30.93ºN	Sahel/Sahara
Palma_de_Mallorca	Spain	2.62ºE	39.55ºN	Mediterranean
Porquerolles	France	6.16ºE	43.00ºN	Mediterranean
Rome_Tor_Vergata	Italy	12.65ºE	41.84ºN	Mediterranean
Saada	Morocco	8.16ºW	31.62ºN	Sahel/Sahara
Santa_Cruz_Tenerife	Spain	16.25ºW	28.47ºN	Sahel/Sahara
SEDE_BOKER	Israel	34.78ºE	30.85ºN	Mediterranean
Seysses	France	1.26ºE	43.50ºN	Mediterranean

Solar_Village	Saudi Arabia	46.40ºE	24.91ºN	Middle East
Tabernas_PSA-DLR	Spain	2.36ºW	37.09ºN	Mediterranean
Tamanrasset_INM	Algeria	5.53ºE	22.79ºN	Sahel/Sahara
Villefranche	France	7.33ºE	43.68ºN	Mediterranean
Xanthi	Greece	24.92ºE	41.15ºN	Mediterranean
Zinder_Airport	Niger	8.99ºE	13.78ºN	Sahel/Sahara
Zouerate-Fennec	Mauritania	12.48ºW	22.75ºN	Sahel/Sahara

Table 10: List of AERONET stations used for forecast evaluation by the Barcelona Dust Forecast Center

Figure 28 shows the NRT evaluation at the AERONET station of Capo_Verde, Cape Verde, in May 2015 and 11 the annual scores 2014-2015 for the whole domain.

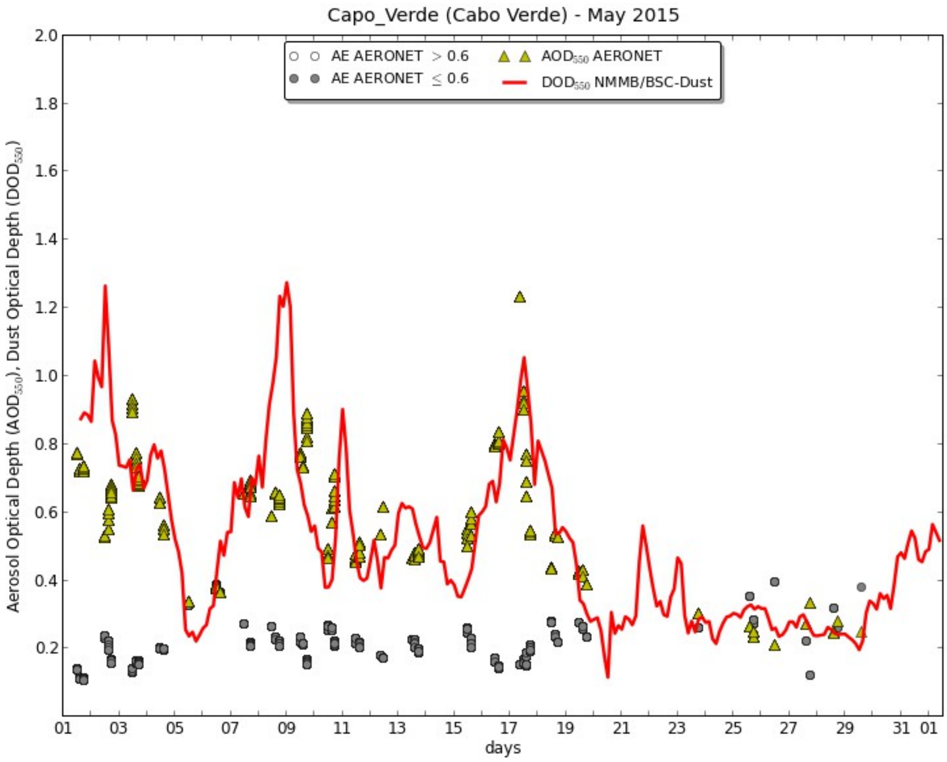

Figure 28: DOD forecast by the Barcelona Dust Forecast Center (full line) compared with AOD (yellow triangles) retrievals from the AERONET station of Capo_Verde (Cape Verde) in May 2015. Black dots show the values of the AE

Year	Mean Bias Error	Root Mean Square Error	Correlation Coefficient	Fractional Gross Error
2014	-0.15	0.35	0.52	0.98
2015	-0.09	0.49	0.53	0.88

Table 11: Annual scores for the DOD forecasts of the Barcelona Dust Forecast Center computed using AERONET AOD retrievals

4.4. Product dissemination

The dissemination of the operational forecasts generated by the Barcelona Dust Forecast Center is performed through three channels: the Centre's website, the WMO's **Global Telecommunications System** (GTS) and the EUMETCast service, which is described below in this Section.

The website (http://dust.aemet.es) provides the last available forecast as well as online access to the Centre’s archive. Pictorial products are available in GIF, but also in KML and KMZ formats, allowing visualization with the Google Earth software. It also presents detailed information on the BDFC, its activity and the operational methods used to generate the daily forecasts.

The forecasts (except those of surface extinction) are also disseminated through the GTS. The bulletin headers follow this format:

PZBcnn **LEMM** dd**1200**

where:

- c=**A** denotes a 0-hour forecast, c=**B** a 3-hour forecast, ..., c=**Y** a 72-hour forecast
- nn=**01** denotes dust surface concentration, nn=**02** dust optical depth, nn=**03** dust dry deposition, nn=**04** dust wet deposition and nn=**05** dust load.
- dd indicates the run's day.

Since 5 November 2015, the forecasts are also disseminated through the **EUMETCast** service. It is a multi-service dissemination system based on standard Digital Video Broadcast (DVB) technology (Figure 29). It uses commercial telecommunication geostationary satellites to multi-cast files (data and products) to a wide user community. EUMETCast service is managed by EUMETSAT and is the European contribution to GEONETCast, which is a global network of satellite-based data dissemination systems coordinated by the intergovernmental Group on Earth Observation (GEO). The BDFC products are distributed on EUMETCast Europe and Africa (channel 12, packet identifier (PID) 301, multi-cast address 224.223.222.35). File name convention is as follows:

- Dust Optical Depth. Forecast of dust optical depth at 550 nm for lead times between 12 and 72 hours every 6 hours: YYYYmmdd**12-3H_SDSWAS_NMMB-BSC-v2_OPER-OD550_DUST-**HH**.gif**.
- Dust Surface Concentration. Forecast of dust surface concentration for lead times between 12 and 72 hours every 6 hours: YYYYddmm**12-3H_SDSWAS_NMMB-BSC-v2_OPER-SCONC_DUST-**HH**.gif**.
- Dust Load. Forecast of columnar dust load for lead times between 12 and 72 hours every 6 hours: YYYYmmdd**12-3H_SDSWAS_NMMB-BSC-v2_OPER-DUST_LOAD-**HH**.gif**.
- Dust Dry Deposition. Forecast of dust dry deposition for lead times between 12 and 72 hours every 6 hours: YYYYddmm**12-3H_SDSWAS_NMMB-BSC-v2_OPER-DUST_DEPD-**HH**.gif**.
- Dust Wet Deposition. Forecast of dust wet deposition for lead times between 12 and 72 hours every 6 hours: YYYYmmdd**12-3H_SDSWAS_NMMB-BSC-v2_OPER-DUST_DEPW-**HH**.gif**.
- Dust Surface Extinction. Forecast of dust surface extinction at 550 nm for lead times between 12 and 72 hours every 6 hours: YYYYmmdd**12-3H_SDSWAS_NMMB-BSC-v2_OPER-DUST_EXT_SFC-**HH**.gif**.

where YYmmdd is the date and HH the forecast lead time.

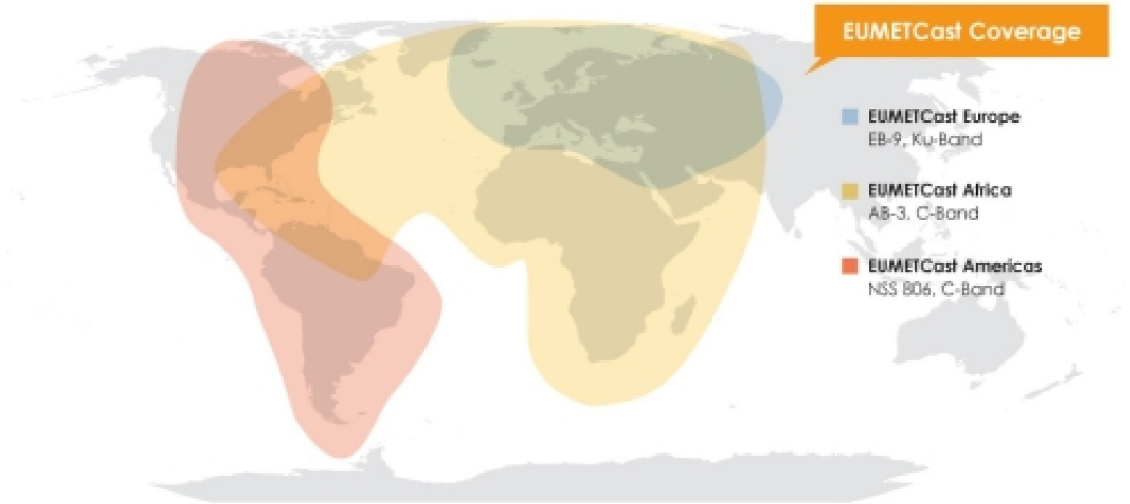

Figure 29: Map of EUMETCast coverage

Users wishing to receive these products should register for 'AEMET Products' via the EUMETSAT's Earth Observation Portal (EOP, https://eoportal.eumetsat.int/userMgmt/login.faces).

4.5. Tailored products

The Centre has made a great effort to understand and meet the needs of the different end-users. In particular, specific products are routinely generated for several NMHSs in the region. As an example, Figure 30 shows a zoom in Mauritania.

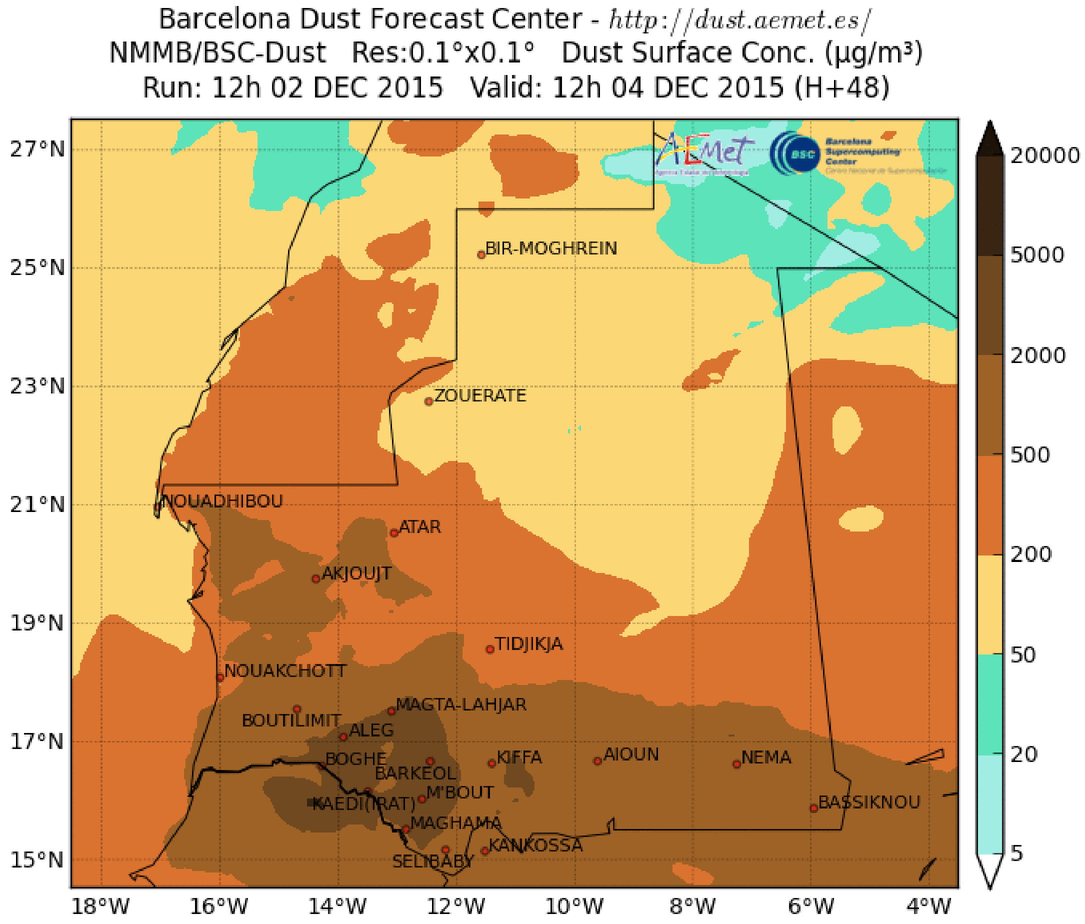

Figure 30: Product generated for the Mauritania's National Office of Meteorology

4.6. Technical structure

The technical structure of the Barcelona Dust Forecast Center is presented following the description of Benincasa et al. (2015).

Two model integrations are daily performed at BSC facilities to ensure the forecast availability:

- The 0.1º x 0.1º x 40 σ-layers resolution forecast (hereafter referred as 0.10º) run at the **Mare Nostrum III Supercomputer** using dedicated resources to ensure the daily execution. This is the default forecast.
- The 0.33º x 0.33º x 24 σ-layers resolution forecast (hereafter referred as 0.33º) run at a dedicated server (**forecast server**). This is the backup forecast.

Both model configurations use initial meteorological conditions from the NCEP global analysis at a 0.5 x 0.5 degree resolution and 6-hourly boundary meteorological conditions from the NCEP Global Forecast System at the same resolution. These files are independently downloaded for both integrations from the NCEP server.

Once completed, forecast data files are uploaded to the **BDFC main server**, where the graphical products are generated and posted on the website. Then, products are transferred to AEMET, where they are ingested into the WMO's GTS, and to EUMETSAT, where they are broadcast through the EUMETCast services.

A system based on Nagios, a free and open-source software, has been implemented to monitor server and network services and notify eventual system issues. An email is sent to the technical staff in case any of the forecasts is unavailable. Moreover, an email summarizing the daily operations is automatically released.

The main characteristics of the three servers are detailed in 12.

	BDFC main server	**Mare Nostrum III Supercomputer**	**Forecast**
Software stack	• Operating System: Linux - openSUSE • Web server: Apache • Application server / Content Management System: Plone	• Operating System: Linux - openSUSE	• Operating System: Linux - openSUSE
Hardware	• CPU: 8 cores Intel Xeon E3-1230 @ 3.2 GHz • Cache size: 8 MB • Memory: 16 GB • Storage: 2 TB • Addressing: 64 bit	• Peak Performance: 1.1 petaflops • 3056 nodes • Memory: 100.8 TB • Storage: 2 PB • Interconnection: Infiniband FDR10 & Gigabit Ethernet • 260 cores reserved to run the model	• 2 nodes with 8 cores Intel Xeon CPU E5420 @ 2.50GHz each • Cache size: 6MB • Memory: 16 GB per node • Storage: 2 TB • Addressing: 64 bit
Recovery	Daily incremental backup of the whole server (IBM Tivoli system) managed by the BSC operations team	Daily incremental backup of the whole server (IBM Tivoli system) managed by the BSC operations team	Daily incremental backup of the whole server (IBM Tivoli system) managed by the BSC operations team

Table 12: Main characteristics of the three servers involved in the BDFC operations

In order to achieve high availability, that is a continuously operational infrastructure for a long length of time, an audit was performed in February 2015 to identify the main vulnerabilities of the operational system. Based upon the results, a plan was set to reduce those vulnerabilities

The main weaknesses detected in the system were:

- The BDFC main server has no redundancy.
- The service depends on BSC resources (connectivity, power supply).
- Both model runs depend on the NCEP meteorological initial and boundary conditions.
- The configuration of the BDFC main server is not suitable to manage peaks with many users and large data traffic.

The main points of the required actions are:

- Redundancy of the BDFC main server. The first solution is to set a slave server continuously synchronized with the master one to redirect the users' requests in case of the master failure. A stronger solution is to duplicate the BDFC main server at AEMET facilities.
- Implementation of the backup model integration outside the BSC network, either at AEMET or at the ECMWF.
- Reduction of the dependency on NCEP meteorological files: the two model configurations should be run with different initial and boundary conditions. Tests have already been done to run the model using meteorological files provided by the ECMWF.
- High-availability configuration: The configuration of the BDFC main server was already improved in April 2015 after an outage due to excessive concurrent accesses. Different configurations are under study to prevent further failures.

4.7. Users

The Barcelona Dust Forecast Center performs quarterly monitoring of the accesses to its web portal. The results (13) show a progressive increase in the number of users and sessions.

Season	Users	Sessions
Mar - May 2014	422	878
Jun - Aug 2014	1.132	2.449
Sep – Nov 2014	1.909	3.175
Dec 2014 – Feb 2015	1.030	2.352
Mar – May 2015	4.012	7.202
Jun – Aug 2015	5.060	7.455
Sep – Nov 2015	10.688	14.569

Table 13: Seasonal accesses to the BDFC web portal

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Appendix 1. List of Acronyms

ACMAD	African Center of Meteorological Applications for Development
AE	Ängström Exponent
AECID	Spanish Agency for International Development Cooperation
AEMET	Spanish State Meteorological Agency
AeroCom	Aerosol Comparisons
AERONET	Aerosol Robotic Network
AOD	Aerosol Optical Depth
BE	Bias Error
BSC	Barcelona Supercomputing Center
CALIOP	Cloud-Aerosol LIdar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol LIdar and Infrared Pathfinder Satellite Observations
CGMS	Coordination Group for Meteorological Satellites
CIMH	Caribbean Institute for Meteorology and Hydrology
CMA	China Meteorological Agency
COP12	Twelfth Session of the Conference of the Parties
CSFA	China State Forestry Administration
DGMAN	Directorate General of Meteorology and Air Navigation of Oman
DMN	National Meteorology Direction of Morocco
DOD	Dust Optical Depth
DSC	Dust Surface Concentration
DVB	Digital Video Broadcast
EARLINET	European Aerosol Research LIdar NETwork
ECMWF	European Centre for Medium-range Weather Forecast
OP	Earth Observation Portal
FAO	Food and Agriculture Organization
FGE	Fractional Gross Error
GEO	Group on Earth Observation
GMES	Global Monitoring for Environment and Security
GTS	Global Telecommunications System
IARC	Izaña Atmospheric Research Center
ICAP	International Cooperative for Aerosol Prediction
IPCC	Intergovernmental Panel on Climate Change
IRI	International Research Institute for Climate and Society
JRC	Joint Research Center
LIDAR	LIght Detection And Ranging
LIRIC	LIdar/Radiometer Inversion Code
MEDARE	MEditerranean climate DAta REscue
MedCOF	Mediterranean Climate Outlook Forum
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NMHS	National Meteorological and Hydrological Service
NOAA	National Oceanic and Atmospheric Administration
MACC	Monitoring Atmospheric Composition and Climate
MPL	Micro-Pulse Lidar
MPLNET	Micro-Pulse Lidar NETwork
NCMS	UAE National Centre for Meteorology and Seismology
NESDIS	National Environmental Satellite Data, and Information Service
NMMB	Non-hydrostatic Multiscale Model on the B-grid

NRT	Near-Real-Time
PID	Packet IDentifier
PM	Particulate Matter
R&D	Research and Development
RA	Reference Area
RGB	Red-Green-Blue
RMSE	Root Mean Square Error
RRTM	Rapid Radiative Transfer Model
RSG	Regional Steering Group
RSMC-ASDF	Regional Specialized Meteorological Center with activity specialization on Atmospheric Sand and Dust Forecast
SDS-WAS	Sand and Dust Storm – Warning advisory and Assessment System
SIP	Science and Implementation Plan
TEOM	Tapered Element Oscillating Micro-balance
TSMS	Turkish State Meteorological Service
UAE	United Arab Emirates
UCAR	University Corporation for Atmospheric Research
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization
WWRP	World Weather Research Programme

Table 14: List of acronyms