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# Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Science and Implementation Plan 2015-2020

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# WORLD METEOROLOGICAL ORGANIZATION

## WORLD WEATHER RESEARCH PROGRAMME

WWRP 2015 - 5

# SAND AND DUST STORM WARNING ADVISORY AND ASSESSMENT SYSTEM (SDS-WAS)

# SCIENCE AND IMPLEMENTATION PLAN 2015-2020

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# 1. MOTIVATION

In its mission as a world leader in weather, climate, water and related environmental issues, the World Meteorological Organization (WMO) contributes to the safety and well being of people throughout the world, and to the societal and economic benefit of all nations. Sand and dust storms (SDS) are recognized by WMO as serious events that can affect climate, weather, environment and health in many parts of the world. WMO therefore has taken a lead with international partners to establish the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) to develop, refine and provide a basis for distributing to the global community products that are useful in reducing the adverse impacts of SDS and to assess impacts of the SDS process on society and nature.

# 2. ATMOSPHERIC DUST

## 2.1 Physical processes

When winds are strong, large amounts of sand and dust are emitted from arid soils into the atmosphere and then transported downwind, affecting areas in the vicinity of dust sources but also regions hundreds to thousands of kilometres away. Drought and wind contribute to the emergence of dust storms, as do poor farming and grazing practices or inadequate water management by exposing the dust and sand to the wind.

Satellite data analysis by Prospero et al. (2002) indicated that most major dust sources are located in arid regions in topographic depressions where deep alluvial deposits have been accumulated. Dust sources include small-scale structures ("hot spots") that substantially contribute to global dust emissions. One of the uncertainties related to sources is the contribution of dust due to human activities. Mahowald et al. (2011) have shown that dust load may have doubled in the 20th century over much of the world due to anthropogenic activities. Recently, Ginoux et al. (2012) mapped dust sources based on satellite observations making distinction between natural, anthropogenic and hydrologic dust sources, where the anthropogenic sources contributes with 25% to global dust emissions. These kinds of maps are key input information for dust modelling assessments and predictions.

A factor of a significant influence on dust emissions and dust impacts to society and environment is the dust grain size distribution. The coarse particles are primarily deposited near the source regions, but finer particles can be transported over distances of intercontinental scales. Dust is removed from the atmosphere through gravitational sedimentation and turbulence, and through scavenging in precipitating clouds. Mineral composition is another important dust feature. Recent work on detailed global mineralogy of arid soils (Nickovic et al. 2012; Journet et al. 2014) provides appropriate input for studying processes affected by the dust mineralogy, such as radiation, health, cloud formation and marine productivity.

Multi-scale meteorological processes are involved in dust emission and transport. Driving meteorological conditions, which control the structure of the dust horizontal and vertical distribution, are cyclones and fronts, low-level jets, haboobs and dust devils and plumes. A more realistic representation of the effects of the smaller-scale meteorological features in dust models is one of the key challenges for the future (e.g. Knippertz and Todd 2012; Vukovic et al. 2014).

### 2.2 Growing research interest for SDS

Due to numerous impacts of dust on health, environment and climate, there is high societal and research interest to better understand the atmospheric dust process, to predict dust and to prevent its unwanted impacts. Figure 1 illustrates the growing interest of the scientific community on dust-relevant research subjects (Stout et al. 2009). The plot shows the distribution of aeolian-research publications from 1645-2005. There are approximately 7000 scientific articles published from 2006-2012 and are available in Google Scholar.

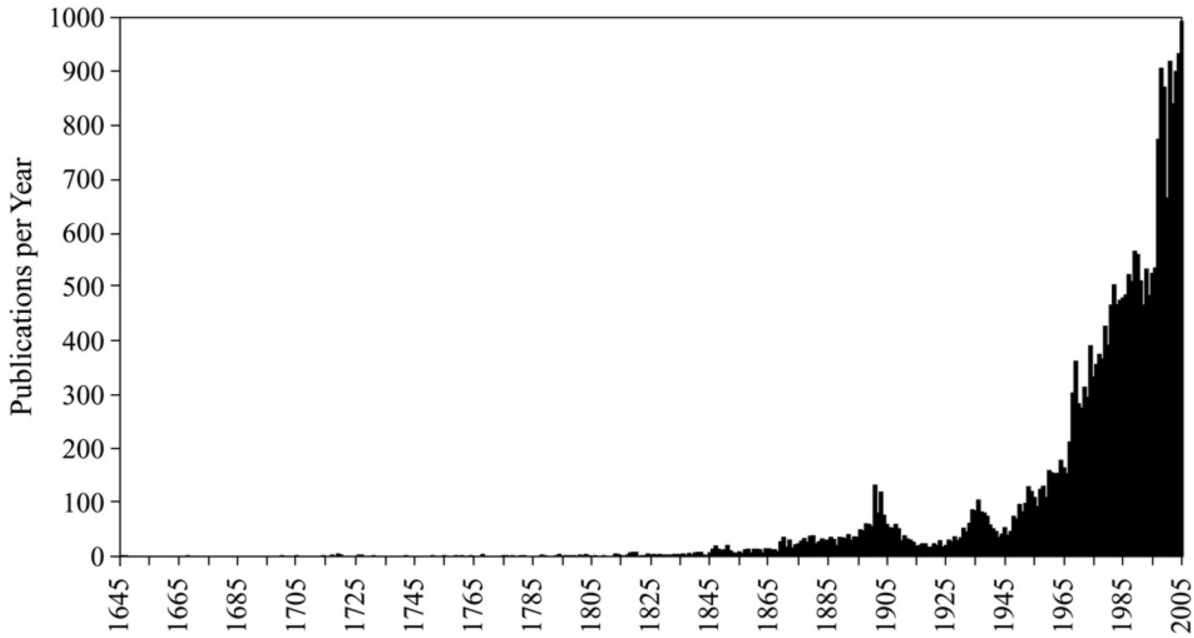


**Figure 1. Publications/year on dust-related subjects (Stout et al. 2009)**

## 3. WMO SAND AND DUST STORM WARNING ADVISORY AND ASSESSMENT SYSTEM

### 3.1 SDS-WAS history

Following the societal needs for monitoring and forecasting SDS, and for assessing its impacts, the WMO launched in 2005 a Sand and Dust Storm Project and created an ad-hoc Steering Committee. More than forty member countries expressed interest in participating in activities to improve capacities for more reliable SDS monitoring, forecasting and assessment.

In 2006, the Steering Committee of the Sand and Dust Storm project proposed the implementation of a Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). In 2007, the 14th WMO Congress endorsed launching of the SDS-WAS project with its mission to enhance the ability of WMO Members to deliver timely and quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities. SDS-WAS is jointly coordinated by the WMO World Weather Research Programme (WWRP) and the Global Atmosphere Watch (GAW).

In 2007, the International Workshop hosted by the Korean Meteorological Administration (KMA) and the WMO/GEO (Group on Earth Observations) Expert Meeting hosted by the Barcelona Supercomputing Center (BSC-CNS) discussed the way forward in SDS-WAS implementation. In June 2008, the 60$^{th}$ Executive Council of WMO (EC-LXI, 2008) welcomed the initiatives towards the development of SDS-WAS as well as the establishment of two SDS-WAS regional centres in China and Spain in support of the corresponding SDS-WAS nodes.

The Regional Steering Group (RSG) for Northern Africa, Middle East and Europe (NA-ME-E) held meetings in Tunis-Carthage, Tunisia (November 2008), Antalya, Turkey (November 2011) and in Castellaneta Marina, Italy (June 2014). The corresponding Regional Centre was created in 2010 in Barcelona, Spain, and it is jointly managed by the Spanish State Meteorological Agency (AEMET) and the BSC-CNS. Its web portal http://sds-was.aemet.es includes: in situ and remote-sensing dust-relevant observations, daily experimental dust forecasts from several organizations, information and training material from several past workshops, and news for the SDS-WAS community. Detailed description on all these issues can be found in its 2010-2012 Activity Report (Terradellas et al. 2014).

The RSG for Asia held meetings in Beijing, China (November 2008), Seoul, Korea (October 2009) and in Tsukuba, Japan (March 2012). The Regional Centre is hosted by the China Meteorological Administration (CMA) in Beijing, China. Its products are available at http://www.wmo.int/pages/prog/arep/wwrp/new/DustforecastsAsianregion.html and at http://eng.weather.gov.cn/dust/product/8002.html.

In 2012, the Regional Centre for the Americas was created in Orange, California, hosted by the Chapman University, and is currently moving to the University of Arizona. Finally, as a result of a recent collaboration between WMO and the United Nations Environment Programme (UNEP), and following a large interest of countries in Western Asia, another possible activity node could be established for this region in the future (Cuevas, 2013).

In May 2013, in view of the demand of many national meteorological services and the good results obtained by the SDS-WAS, which proves the feasibility and the need to begin developing operational services beyond the scope of research and development (R&D), the WMO Executive Council designated the consortium formed by AEMET and the BSC-CNS to create in Barcelona the first Regional Specialized Meteorological Center with activity specialization on Atmospheric Sand and Dust Forecast (RSMC-ASDF). The Centre, which started operations in March 2014, generates and distributes operational predictions for Northern Africa (north of equator), Middle East and Europe.

Despite the start of operational services, numerous areas in which further research and development is necessary have been identified and are described in the following sections.

### 3.2 SDS-WAS achievements

In addition to developing methods to supply observational and forecast products, as well as other relevant SDS information, several other objectives have also been achieved:

- AEMET established several new ground aerosol measurement stations in Northern Africa.
- A number of SDS-WAS user-oriented training workshops and scientific meetings were organized to promote the SDS-WAS project.
- Multi-model ensemble products have been established within the NA-ME-E node and publicly made available on the website.
- On-line model evaluation of the model products against observations and on-line model inter-comparison has been established within the NA-ME-E node.
- SDS-WAS participated as a partner in several research initiatives, including the Meningitis Environmental Risk Information Technologies (MERIT) project, the Group of Experts on Scientific Aspects of Marine Environmental Protection (GESAMP) project and the WMO project with UNEP[a].
- Formal designation by the WMO Executive Council of AEMET and BSC-CNS (Spain) to host a RSMC with activity specialization in Atmospheric Sand and Dust storm Forecasts (RSMC-ASDF) for Northern Africa, Middle East and Europe. With this designation, a part of the SDS-WAS research activities are technologically transferred to operations becoming so a component of the Commission for Basic Systems (CBS).
- Regional dust model re-forecast over the NA-ME-E region for the period 1979-2010.
- Studying dust deposition over the open ocean and its impacts on marine bio-productivity (Schulz et al. 2012) through collaboration with GESAMP.
- Studying impacts of dusty weather conditions on meningitis outbreaks in Africa within the European Union Monitoring Atmospheric Composition and Climate (EU MACC) project, the WMO THORPEX (THe Observing system Research and Predictability EXperiment) project, and in collaboration with the World Health Organization (WHO).

### 3.3 Current collaborative projects

SDS-WAS initiated several collaborative research projects, in which different interested organizations are taking part. These projects are aimed to study in more details particular cases and/or to better understand the features of the atmospheric dust process. As a follow-up of these initiatives, corresponding scientific reports (and possibly scientific articles) will be published. The following collaborative projects are ongoing:

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[a] WMO/UNEP Project *"Establishing WMO SDS-WAS Regional Node over West Asia: Current Capabilities and Needs to Build Capacity for SDS Monitoring, Warnings and Services in the Region"*

- ***Participation in MACC (MACC-II and MACC-III) project***

Participation in the Validation (VAL) sub-project of the European Monitoring Atmospheric Composition and Climate (MACC) project in two different phases (MACC-II and MAC-III). Currently MACC-III- Interim Implementation - is the current pre-operational Copernicus Atmosphere Service. The role in MACC-III VAL sub-project is providing dust evaluation and quality assessment of MACC-Dust model using dust products (AOD and DOD) from the SDS WAS RC NA-ME-E median multi-model product, AErosol RObotic NETwork (AERONET) and satellite-based dust data. Quarterly Near-Real-Time (NRT) and semiannual Reanalysis (REA) validation reports from early 2012 to date. https://www.gmes-atmosphere.eu/services/aqac/global_verification/
*Contact: Emilio Cuevas (Email: ecuevasa@aemet.es)*

- ***Supporting the CALIMA field experiment***

The Hydrometeorological Service of Serbia, Belgrade, Serbia supported the CALIMA (Cloud Affecting particles In Mineral dust from the Sahara) August 2013 and August 2014 field campaigns conducted by the Swiss Federal Institute of Technology (ETH) Zürich, Switzerland and the Izaña Atmospheric Research Centre (AEMET), Spain, by performing a modelling experiment aimed at predicting atmospheric ice nucleation as affected by chemistry and mineralogy of dust aerosol in the Saharan Air Layer (SAL). http://aerosoli.com/
*Contact: Slobodan Nickovic (Email: nickovic@gmail.com)*

- ***Capacity building project in collaboration with other institutions and National Meteorological and Hydrological Services***

The SDS WAS Regional Centre NA-ME-E has coordinated with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and meteorological services 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 programme. A series of training courses and seminars have been coordinated:

- Training week on Satellite Meteorology (Barcelona, Spain, 8-12 November 2010)
- Lectures on Atmospheric Mineral Dust and its Impacts 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 (satellite and ground observation and modelling of atmospheric dust) (Antalya, Turkey, 21-25 November 2011
- II Lectures on Atmospheric Mineral dust (Barcelona, Spain, 5-9 November 2012)
- 3rd Training Course on WMO SDS-WAS products (satellite and ground observation and modelling of atmospheric dust) (Muscat, Oman, 8-12 December 2013)

Other training courses within the Regional Node:

- Meteorological Services, Sand and Dust Storm (SDS), Forecasting and Early Warning System (Istanbul, Turkey, 22-26 February 2011)

- WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) hand-on training workshop on dust modelling, (Belgrade, Serbia, 8-12 October 2012)
- Cours sur l'utilisation des produits satellitaires aux applications agrometeorologiques (Niamey, Niger, 19-23 November 2012)
- Workshop on Meteorology, Sand and Dust Storm (SDS), Combating Desertification and Erosion (Ankara, 26-28 November 2012)
- Training Course on the Use of Satellite Products for Agrometeorological Applications (Accra, Ghana, 10-14 June 2013)
- Workshop on Meteorology, Sand and Dust Storm, Combating Desertification and Erosion (Istanbul, Turkey, 28-31 October 2013)
- McIdas tutorial with focus on atmospheric dust cases (Muscat, Oman, 15-16 December 2013)
- Cours sur l'utilisation des produits satellitaires aux applications agrometeorologiques (Ouagadougou, Burkina Faso, 5-9 May 2014)

*Contact: Enric Terradellas (Email: eterradellasj@aemet.es)*

- ***Training stays in the SDS WAS Regional Centre NA-ME-E***
  - Expert from the Turkish State Meteorological Service, from 1 January to 3 May 2013, trained in training in transport modelling of mineral dust
  - Expert from the faculty of Sciences, University Al- Mustansiriya, Bagdad-Iraq, from 1 June to 30 November 2014; trained in transport modelling of mineral dust

*Contact: Jose María Baldasano (Email: jose.baldasano@bsc.es) and Sara Basart (Email: sara.basart@bsc.es)*

- ***Forecasting the North African dust outbreak towards Europe occurred in April 2011***

Four state-of-the-art dust forecast models are 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 is assessed by comparing their results with aerosol optical depth from AERONET and from the Moderate Resolution Imaging Spectroradiometer (MODIS), as well as with dust surface concentration from air-quality monitoring stations. In addition, the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) vertical profiles of extinction are used to examine the predicted vertical dust distribution of each model. To identify possible reasons for the different model performance, the simulated wind fields are evaluated with 10-m winds observed at meteorological stations and the vertical wind profiles from two radio sounding stations in the source region.
*Contact: Nicolás Huneeus (Email: nhuneeus@dgf.uchile.cl)*

- ***Dust model - lidar comparison***

Dust concentration forecast by different numerical models will be compared with retrievals from lidar co-located with sun photometers using the Lidar/Radiometer Inversion Code (LIRIC) algorithm. LIRIC 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 aerosol in the atmosphere in two types: fine mode (e.g. smoke, urban pollution) and coarse mode (e.g. desert or volcanic dust, marine aerosol); if lidar depolarization measurements are also available, the coarse mode is further divided in two sub-modes, coarse/spherical (e.g. marine) and coarse/non-spherical (dust). 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. We can thus separate the dust components of the measured aerosol and make the comparison with dust model simulations more straight forward.
*Contact: Ioannis Binietoglou (Email: ioannis@inoe.ro)*

- ***Study of a haboob in Iran***

It is proposed to conduct a in-depth case study of the small-scale extreme dust storm occurred in Tehran on 2nd June 2014, at 5:30 p.m. local time, lasting less than 2 hours according to public evidence. Based on public news, the dust storm caused several deaths, reduction of visibility to several tenths meters in the city, and adverse disturbance of the public traffic. The blowing wind reached 110 km/h.

According to public information and limited observations currently available, it is hypothesized that the dust storm passing Tehran was generated by a small-scale atmospheric circulation such as a squall line or convective downdraft.

This project proposal is a response to the discussion of the SDS-WAS RSG for NA-ME-E during its regular meeting held in Italy on 4th June 2014, on the Tehran event. The RSG noted that eight dust models, routinely operated within the SDS-WAS NA-ME-E Regional Node, predicted an increase of dust concentration in a wider 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 storm.
*Contact: Slobodan Nickovic (Email: nickovic@gmail.com)*

## 3.4 SDS-WAS objectives

The following objectives will be the axis around which the activities of SDS-WAS will be articulated during the period 2015-2020:

- Facilitating collaboration and coordination at regional and global scale between SDS-WAS partners and initiating joint research projects for improving dust observations and modelling.
- Encouraging experimental provision of near-real-time forecasts, models validation and models intercomparison.
- In collaboration with other WMO technical commissions, supporting transfer of the SDS-WAS research observational and forecasting facilities to operational technology and to applications relevant for users.
- Providing training on use of the SDS-WAS research outcomes.

- Building bridges between SDS-WAS and other communities conducting aerosol-related studies (air quality, biomass burning, etc.).
- Participating in international multi-disciplinary research initiatives such as including MERIT (http://merit.hc-foundation.org/) and GESAMP (http://www.gesamp.org/).
- Links with the EU-funded Copernicus Atmosphere and Monitoring Services for the NA-ME-E node.
- Links with satellite agencies (European Space Agency (ESA), EUMETSAT, Japan Aerospace Exploration Agency (JAXA), National Aeronautics and Space Administration (NASA), etc).
- Links with ground-based networks (Aerosols, Clouds, and Trace gases Research InfraStructure Network (ACTRIS), GAW, etc).

# 4. SDS-WAS GOVERNANCE

## 4.1 Global coordination

The SDS-WAS activities at the global scale are coordinated by the SDS-WAS Steering Committee (SDS-WAS SC) as described in Resolution 13 - Sand and Dust Storm Warning Advisory and Assessment System of the EC-66[b] (see Annex 1)

The SC's role is to:

- Coordinate SDS-WAS activities between regional SDS-WAS activity nodes (see below Regional coordination)
- Define research policy of SDS-WAS and update regularly
- Integrate regionally-based research
- Provide guidance on the standardization of activities at regional level
- Identify research gaps in SDS-WAS activities at global scale and recommend solutions
- Monitor and provide periodic reviews on the fulfillment of the research objectives as specified in the plan for the SDS-WAS implementation
- Encourage global activities in research and assessment and promote their implementation
- Encourage contributions to a WMO Trust fund for SDS-WAS
- Report to WWRP SSC and inform EPAC SSC

## 4.2 Regional coordination

At the regional level, SDS-WAS is structured as a federation of regional partners. The collaboration is realized through regional activity nodes, which are self-organized structures with a high level of autonomy.

[b] *The Executive Council Sixty-sixth session, Geneva, 18-27 June 2014. Abridged final report with resolutions. WMO-No. 1136, ISBN 978-92-63-11136-4. Resolution 13 (EC-66) – Sand and Dust Storm Warning Advisory and Assessment System*

The organization of regional nodes allows flexibility, growth and evolution, while preserving the autonomy of individual institutions. It involves a variety of participants (universities research organizations, meteorological services, health organizations, etc.) gathered to cooperate and benefit without requiring changes to their own internal structures and existing arrangements. The partners of a regional node will agree on minimum regional standards to cooperate. Nodes will be open to new members to join.

Research activities within each node are defined and led by a SDS-WAS RSG and coordinated by a Regional Centre (Figure 2).

There are three SDS-WAS regional activity nodes already established by 2014:

- Regional Node for Asia, coordinated by a Regional Centre hosted by the CMA (Beijing, China)
- Regional Node for NA-ME-E, coordinated by the Regional Centre as a consortium of AEMET and the BSC-CNS, from Spain
- Pan-American Regional Node hosted by the University of Arizona (USA)

As described above, a group of interested countries have proposed the establishment of a new SDS-WAS activity node for Western Asia.

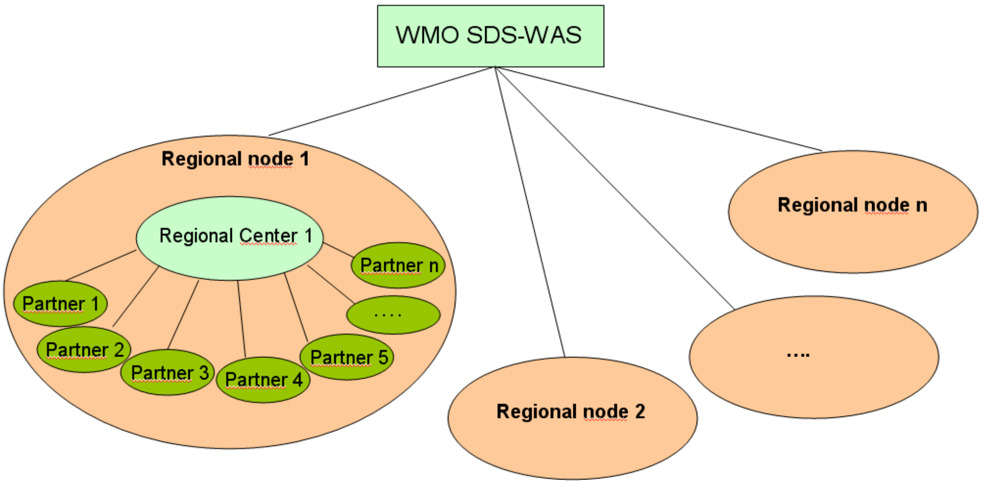


**Figure 2. The SDS-WAS structure**

## 4.3 Membership in Steering Committee and Regional Steering Group

SC Chairperson and members of the SC will be nominated as described in Resolution 13 - Sand and Dust Storm Warning Advisory and Assessment System of the EC-66 (see Annex 1).

Selection of chairpersons and members of a RSG will be made through an agreed decision of partners of a particular region.

Members of SC and RSGs and chairpersons of RSGs will be nominated for a 4 year period, with a possibility to extend the membership for another 4 year period.

In general, SC and RSG membership will reflect diverse scientific expertise, and secure gender balance.

# 5. SDS-WAS IMPLEMENTATION ISSUES

## 5.1 Improvement of the node portals

The web portals of the regional nodes will be designed to allow the user access to observational and forecast products, as well as to sources of basic information. In particular, they will provide National Meteorological and Hydrological Services (NMHS) with the necessary information to issue operational predictions and warning advisories related to the dust content in the atmosphere. In the case of web portals that already are fully operational, as that of the Regional Node for NA-ME-E (http://sds-was.aemet.es), efforts will be aimed to progressively increase the amount and quality of the contents published, with special emphasis on observational and forecast products.

Access to data from global, regional and national observational networks is crucial to any forecast and early-warning system for real-time monitoring, validation and evaluation of forecast products. Access to dust forecasts issued by different numerical models shall also be provided. In addition to observational and forecast products, the web portals should offer miscellaneous information on actions carried out within the framework of the WMO SDS-WAS as well as on resources, news and events that are related to its subject.

## 5.2 Establishing the West Asian node

Sand and dust storms are a major problem in West Asia, a region that is part of the well-known “dust belt” stretching from the Western Sahara to central and eastern Asia. However, the main characteristics of dust events in this region (intensity, extent and frequency) are not well known or, at least, have not yet been addressed in a scientific and systematic way (Cuevas, 2013).

Severe dust events affecting the population are very frequently caused by mesoscale convective systems making necessary the development and implementation of ad-hoc high resolution dust modelling. Furthermore, the usual coexistence of desert mineral dust with industrial aerosols from petrochemical activities constitutes a challenging problem. Unfortunately, neither the ground-based observation networks are sufficiently comprehensive nor the network topologies the most suitable to perform a detailed spatial-temporal analysis of this characteristic aerosol distribution.

Global warming has the potential to cause major changes in dust emissions. IPCC (2007) suggests that, under most scenarios, many dry-land areas will suffer from lower rainfall regimes and drier terrains because of higher rates of evapotranspiration. This will favour the formation of shallow soils that are often characterized by a high content of airborne particles. Therefore, there is a likelihood of increased dust storm activity, though this conclusion depends on how winds may change - a matter of great uncertainty.

All these particular circumstances should encourage the creation of a SDS-WAS regional node for West Asia. NMHS, environment protection agencies, health institutions, aviation authorities, energy departments, marine resources and fishery agencies, wildlife, forestry and agriculture agencies, disaster risk and civil protection agencies, research institutions and universities should participate in the SDS-WAS regional node as contributors and/or as specialized users (Cuevas, 2013).

## 6. SDS-WAS RESEARCH TOPICS

### 6.1 Model evaluation and intercomparisons

A fundamental step in dust forecast is the model evaluation. This process consists in the comparison of the model results with the available observations on different temporal and spatial scales. It facilitates the understanding of the model's capabilities, limitations, and appropriateness for the purpose for which it was developed. In this framework, there are three primary objectives:

1) Evaluate quantitatively and qualitatively whether the modelling system is successfully predicting the temporal and spatial evolution of a particular process.
2) Explore the adequacy and correctness of the methods implemented in the model; comparison with other models in addition to the observations can be helpful in identifying the strength and weakness of the system.
3) The evaluation results should lead to new directions in model development and improvement.

An evaluation process should be an intrinsic part of an operational forecast system and is therefore done on a regular basis on a time scale known as NRT. The end result is the quantification of confidence and predictive accuracy of the forecast products. An additional and different evaluation is where the model's performance to simulate a given event or an annual cycle is examined in depth. This case study evaluation can be made any time after the forecasted period and observations that were not available for the NRT evaluation can be included; the purpose is to identify potential areas to improve the model. Direct-sun photometric measurements are a powerful tool for remote sensing of the atmosphere allowing retrieval of column-integrated aerosol microphysical and optical properties, very useful for point dust model evaluation. In particular, AERONET is a comprehensive set of continental and coastal sites complemented with several sparsely-distributed oceanic stations that provides large and refined datasets at NRT (Holben et al. 1998; Dubovik and King, 2000). Properties such as AOD that integrate the contribution of different aerosol types are complemented with spectral information that allows hypotheses about its nature (Dubovik et al. 2002). A major shortcoming of these measurements is its unavailability with cloudy skies and during nightime. However, these measurements are by far the most commonly used in dust model evaluation. Lidar and last generation of ceilometers are the only tools capable of inquiring about the vertical profiles of aerosol-related variables and therefore evaluate this model component.

Model intercomparison is the process to assess a model performance by simultaneous comparison of modelling results provided by different models for the chosen situations. The differences in model results can reveal the strengths and weaknesses of particular modules or parameterizations schemes and can help to characterize conceptual uncertainties arising from the choice and implementation of the physical models applied. A key point in the evaluation process or intercomparison is the computation of metrics defined to provide a quantitative characterization of the agreement between model results and observations over specific geographical regions and time periods.

### 6.2 High-resolution dust modelling (1-3 km)

The spatial resolution of the dust models has followed a similar evolution as that of the numerical weather prediction (NWP) models. The development of non-hydrostatic models, with the transport equation of mineral dust added as on-line component, will allow substantial improving the horizontal resolution from several tens of km to less than 10 km.

The current challenges consist of improving the representation of the model dynamics and the physical processes of dust emission and deposition, necessary to run the models at finer resolutions, approaching 1 km, and allowing to properly simulate local-scale phenomena such as haboobs, density currents and squall lines. At that high resolution, conventional identification of sources based on preferential sources and static data based on lend cover appears not to be sufficient to take into account dust emissions from short-living hot spots. Sundram et al. (2004) stated that simulation of individual small-scale dust events required use of high-resolution data on agricultural areas as dust productive sources. Extensive studies over the Sahara region also highlighted the relevance of use of high-resolution numerical models for simulation of small-scale dust events (e.g. Knippertz et al. 2009; Solomos et al. 2012; Tegen et al. 2013).

The simulation of a haboob dust storm over Phoenix (USA) generated by local dust hot spots and driven by a cold convective-storm downburst was not successful before the following modelling components are introduced (Vukovic et al. 2014):

- Dust model downscaled to 4 km
- Non-hydrostatic solver
- Explicit cloud resolution
- Definition of the dust source mask based on combined use of the most recent satellite data on land cover and normalized difference vegetation index (NDVI) data

This study provides guidance to possible developments of a new-generation of dust models, anticipating that corresponding computer resources could support the execution of such models. Nested models that apply the high resolution to the potential dust source regions or finding appropriate parameterization to describe such high resolved events by larger scale model fields should be tested.

### 6.3 Data assimilation

The quality of aerosol re-analysis and forecasting depends on the dynamics of the forecast model and on the physical parameterization of aerosol processes. However, it is difficult to have exact emission sources, and models that reproduce physically-based emission processes. Remote sensing observations from satellites and from conventional sensors can improve the process characterization. Data assimilation provides a tool to feed observations into the atmospheric models and provide improved initial conditions for such models. In particular, the assimilation of aerosol-related observations aims to provide the optimal estimate of the true aerosol burden in the atmosphere. Aerosol data assimilation is a relatively new field of research. Current data assimilation systems do not necessarily have an aerosol data assimilation capability and aerosols are produced uniquely from their surface emission fluxes. However, since the first attempts made in the early 2000s with Optimal Interpolation techniques (Collins et al. 2001), the major NWP centres and several research institutes have recently invested their resources into building the assimilation of aerosol-related observations into their systems either through variational techniques like 3DVar (e.g. at the US Naval Research Laboratory (NRL)) and 4DVar (e.g. at the European Centre for Medium-Range Weather Forecasts (ECMWF), Benedetti at al. 2009), or ensemble Kalman Filter techniques (e.g. at the Japan Meteorological Agency (JMA), Sekiyama et al. 2010). The main efforts in the field have been in the assimilation of retrieval products (i.e. atmospheric parameters inferred from raw measurements), such as AOD retrieved from satellite reflectances or from measurements from ground-based sun photometers. Currently, the most limiting aspect in the dust model data assimilation is the impossibility to operationally use lidar (and potentially ceilometer) observations as well as satellite aerosol vertical profiles in order to further improve dust forecasts. Although there are some initial promising non-operational experiments to insert vertical profiles (e.g. at JMA), more effort should be made to better represent the initial vertical dust structure in the prediction models.

### 6.4 Chemical and physical characterization of dust and its optical properties

Mineral dust aerosol affects the atmospheric radiation budget through absorption and scattering of incoming solar radiation, and absorption and reemission of outgoing long-wave radiation. Several works have indicated the relevance of the absorbing properties of mineral dust (Kaufman et al. 2001; Moulin et al. 2001; Haywood et al. 2003). However, it is not clear the degree in which mineral dust cools or warms the atmosphere (IPCC, 2013). The mineralogical composition of dust aerosols is a key factor to properly determine the sign of the radiative forcing. Dust particles are mainly constitute of oxides (SiO2, Al2O3, FeO, Fe2O3, CaO, and others) and carbonates (CaCO3, MgCO3). Models generally treat the dust aerosol as a homogeneous particle with specific size distribution and optical properties. Such optical properties strongly vary on the composition of the dust. Thus, large uncertainties are currently present in models due to the homogeneous treatment of the aerosol. Some works have discussed the main sensitivities of the dust radiative perturbation to its mineralogical content (Liao and Seinfeld, 1998; Balkanski et al. 2007; Moosmüller et al.

2012), shape (Räisänen et al. 2013), or their vertical distribution (Zhang et al. 2013). Balkanski et al. (2007) studied the sensitivity of mineral dust radiative effect on the refractive index. The authors considered the mineralogy of the dust aerosol, and found a much better agreement with radiative forcing measurements. Balkanski et al. (2007) results indicate that dust is less absorbing than previously assumed, and point out the significance of properly characterize the mineralogical composition and the refrective indices of the dust aerosol to estimate its radiative forcing. For proper representation of dust optical properties, mineralogy information should be included.

### 6.5 Dust re-analysis

Dust re-analyses are required to perform climate studies. Re-analysis allows obtaining dust spatio-temporal distributions and climatology, which are particularly important where no observations are available. Coupled with weather information such simulations provide insight into dust generation and transport processes. Re-analyses also provide insight into seasonal, inter-annual and long-term atmospheric dust variations, and relate them with potential changes in weather patterns.

Long-term dust-related observations and model re-analysis could be used in several health-related applications, such as epidemiological studies, or to perform feasibility studies of future solar power plants in arid and desert regions by obtaining maps of solar radiation attenuation by mineral dust in suspension, or in ocean research to relate dust deposition with chlorophyll records, among others (Cuevas et al. 2014).

A good example is the dust re-forecast performed by the BSC, Barcelona, for the period 1979-2010 using the NMMB/BSC-Dust model with a horizontal resolution of 0.5° x 0.5° ((http://sds-was.aemet.es/forecast-products/reanalysis).

Dust-related re-analyses will be an essential component in databases of future climate services. Computational resources to run and archive long-term dust re-analyses with global and regional models are needed.

### 6.6 Dust interaction with radiation and clouds and impacts to weather and climate

Dust aerosols impact the climate system by influencing the radiation budget, cloud processes, and various biogeochemical cycles. The radiation balance of the Earth system is affected by the scattering and absorption of solar and infrared radiation by mineral aerosols (Miller and Tegen, 1998; Sokolik and Toon, 1999). Both magnitude and sign of radiative forcing of dust are considered to be one of the most uncertain aspects in determining the net radiative forcing from natural and anthropogenic aerosols (IPCC, 2013).

Furthermore, dust aerosol can act as ice nuclei (IN) affecting the cloud properties (increasing albedo) and lifetime and the radiative fluxes. While the important role of aerosols in climate models has long been recognized, its impact on short-term weather forecasts has been less investigated and so it is less well known (Grell and Baklanov, 2011; Mulcahy et al. 2014). Some works have focus on the impact of dust aerosol on the radiative balance of NWP models (e.g. Pérez et al.

2006; Spyrou et al. 2013; Kong et al. 2014) showing significant impact under strong dust outbreaks over the Mediterranean area.

Less understanding exists in the role of dust aerosol as IN and its impact on NWP models. A better treatment of cloud formation and online coupling of meteorological and aerosol dynamics models will have a strong positive impact on weather forecasting and climate studying, but more research in the ice nucleation on dust aerosols is needed.

### 6.7 Studying further dust impacts

For countries in and downwind of arid regions, airborne sand and dust presents serious risks to the human health, environment and economy.

Impacts on health include respiratory and cardio-vascular problems, eye infections and in some regions, diseases such as meningitis and valley fever (WHO, 2006; Sprigg et al. 2014). Dust can carry spores, bacteria, viruses and persistent organic pollutants. It can also transport nutrients to parts of the world oceans and enhance marine bio-production. Identifying the time and place when/where particular matter (PM) aerosol exceeds air quality standards, particularly when dust is a dominating component, is important for the human health. For example, NASA sponsored projects PHAiRS (Public Health Applications in Remote Sensing) and ENPHASYS (ENvironmental Public Health Application SYStems) projects (Morain et al. 2007, 2009; Sprigg et al. 2008, 2012) were focused on studying impacts of dust fine particulates on population health in the Southwest of the USA and how to predict such conditions. At a global scale, the effect of long-term exposure of population and mortality was studied by Giannadaki et al. (2014).

Predicting SDS can also help to explore and better understand the hypothesized role of mineral dust in outbreaks of meningitis across the Sahel's "meningitis belt." (Thomson et al. 2006; Pérez et al. 2014). WHO, WMO, GEO and other organizations through the Meningitis Environmental Risk Information Technologies are supporting international research that also includes many African countries to further investigate this issue. SDS-WAS has been recognized as a source for useful information to predict high risk for meningitis outbreaks in specific regions of the Sahel. Testing the iron hypothesis is also a research issue that could be considered. According to this hypothesis, the Neisseria bacteria would need iron to grow and become virulent (Noinaj et al. 2012). Dust models including mineralogical information could be research tools useful to test the hypothesis.

Regions affected by dust storms suffer frequent and serious problems in road and air transportation, and negative impacts on agriculture causing loss of crop and livestock (Stefanski and Sivakumar, 2009). Dust transports nutrients to land and oceanic regions affecting positively biomass production (Mahowald et al. 2005; Schulz et al. 2012; Nickovic et al. 2013). Dust air masses can also transport contaminants, pesticides or trace metals playing then a negative effect producing a degradation of ecosystems (Garrison et al. 2006). Mineral dust is one of the major contributors to Earth's radiative balance through notable radiation backscattering (Tegen et al. 1996; Mahowald et al. 2006; IPCC, 2013). This seems to have played an important role in amplifying past climate changes (Jansen et al. 2007). Mineral dust might attenuate the Direct Normal Irradiance (DNI) impacting in solar energy (Gueymard, 2012).

Dust particles have important effects on weather and climate through interaction on clouds microphysics and life cycle, by generating large concentrations of cloud condensation nuclei and ice nuclei (Hoose and Möhler, 2012), which lead to impact on the droplet size, cloud albedo and lifetime (Hansen et al., 1997). However, despite the importance of ice formation in determining the properties of clouds, the Intergovernmental Panel on Climate Change (IPCC, 2007) was unable to assess the impact of atmospheric ice formation in their most recent report because our basic knowledge is insufficient.

Recent studies indicate that dust plays a very important role in the formation of cold clouds (Cziczo et al. 2013). Mineral dust (together with metallic particles is the dominant source of residual particles in cirrus clouds, 61% by number. Further, measurements suggest heterogeneous freezing (freezing due to aerosol) is the dominant formation mechanism of these clouds, contributing with 94%. In the process of cold cloud formation, mineral composition of dust plays a very important role. A recent study of Atkinson et al. (2013) shows that among dust minerals, feldspar is the most efficient ice nucleation agent.

Finally, due to multiple connections with the Earth's systems, mineral dust can also impact the carbon cycle (Jickells et al. 2005; Hamza et al. 2011).

Studies on different impacts caused by mineral dust should be object of attention and continuous support by the WMO SDS-WAS. The achievement of new dust-related R&D results, relevant to different social, economic and scientific communities, as well as continuous communication and information exchange with end users should be a priority of WMO SDS-WAS.

### 6.8 Dust observation techniques and methodologies

Dust observations play a key role in the SDS-WAS activities: data for near real time monitoring, model data verification/validation, model data assimilation, and regional aerosol characterization are essential inputs from the observation "community".

However, there are important observational constraints that prevent adequate characterization of mineral dust, and accurate assessment of dust model outputs as well as observations from satellites. These are the following:

1) The scarcity of in situ (PM10, visibility) and remote sensing (sunphotometers, lidars and ceilometers) observations in vast desert dust source regions as Northern Africa, Middle East, and East Asia imposes significant limitations on the characterization and monitoring of mineral dust. The problem of observation skills is amplified in dust source regions where high ground reflectance adversely affects satellite observations from passive sensors operating at visible wavelengths, so that dust observations are either not feasible or suffer

from large errors. The installation of ground-based sampling and observation systems in remote sites is not an easy task. However, some existing WMO GAW stations, and others from associated networks (i.e. AERONET) located in or near dust source regions could serve as a basis to implement and reinforce new observation programs through capacity building actions. The development of new robust, automated and inexpensive instrumentation will help to implement dust observation networks in remote areas. The development of new multispectral and the use multi-angle polarization satellite sensors will improve detection and monitoring of mineral dust required for both operational prediction tasks as research activities. Much is also expected from space-borne active sensing instruments such as lidars and from infrared sensors (interferometers and high-resolution spectrometers) which have sensitivity to dust particles.

2) The evaluation of mineral dust is a complex mission because dust is one of the many types of aerosols that can be found mixed in the atmosphere. An important limitation of model validation is the uncertainty associated with dust observations. In fact, at present there are no instruments for in situ (i.e. PM10) and atmospheric column observations (i.e. AOD, vertical extinction) which provide direct measurements of dust. Those provide in fact the total content of aerosols. Dust is estimated from aerosols observations using additional auxiliary parameters and making a number of assumptions. The development of new techniques and methodologies focused on identifying and quantifying the contribution of dust to the total aerosol content is indispensable in order to improve dust observations, and thus, data assimilation and model validation.

3) Vertical profiling for dust is needed since this can be also used as a bridge between in situ observations and satellite observations (WMO-CAS Technical Conference, November 2013). Latest technology developments allow automated lidar and ceilometer systems for continuous operation which could be remotely controlled. This might fill gaps of dust vertical distribution in remote areas, thus achieving a balance between research and operational observations.

4) Development of new techniques and methodologies for the automatic quantification of dry and wet deposition of dust is necessary, both for the validation of the deposition given by the models, and also to assess the impact on ecosystems, especially in the ocean, wherein a relationship between the proliferation of algae and phytoplankton, and nutrients (Fe, P) transported by mineral dust exists.

5) A clear lack in in situ measurements for dust fluxes and wind erosion processes in dust sources (i.e. the Saharan, Arabian and East Asia deserts) is clearly identified. Present dust models generally describe the spatial and temporal evolution of the dust size distribution from the sources to the deposition areas. However vertical dust mass fluxes are not sufficient to constrain the simulated dust emission. So, it is absolutely necessary to initiate in situ measurement programs to understand and estimate vertical dust mass fluxes and saltation. New instruments and methodologies have been recently developed within the Sino-Japanese joint project Aeolian Dust Experiment on Climate impact (ADEC), such as a new sand particle counter (SPC) to measure the saltation process and a new method that implies to measure dust concentration, at least at two levels, and dynamic parameters (wind velocity and temperature profiles), in order to compute U* and stability correction in

the field. The observation “community” is encouraged to implement new programmes in or near dust sources which will help to improve knowledge of dust generation mechanisms and help modelling dust sources.

6). Dust is a term referring to a mixture of a wide variety of minerals. Minerals each have different physical (size spectrum, particle shape, density, hygroscopicity, spectral refractive indices) and chemical properties (chemical reactivity), and therefore play different roles in radiative forcing (Sokolik et al. 1998), and as cloud condensation nuclei and ice nuclei. The abundance of various constituents depends on the region of dust origin, how it was mobilized, chemical and physical transformation processes during its transport, and degree of mixing with pollutants.

Bulk chemical characterization is the most widely used technique for identifying and quantifying the presence of dust (Rodríguez et al. 2012). Variability in dust composition is often used to identify dust sources, and to assess the degree of mixing with pollutants, what is crucial in some regions (i.e. Middle East and East Asia). When dust mixes with pollution aerosols (e.g. ammonium-sulfate), they originally present an ‘external mixing’ state. However, over time, these populations tend to evolve such way most of particles tend to have a similar composition as a function of their size (Raes et al. 2000). Some recently developed techniques (e.g. mass spectrometers, or automatic elemental composition analysis) could be incorporated into long term measurement programs during specific periods every year (e.g. dust season) (Rodríguez et al. 2012), what might be of great help to validate high-resolution mineralogical databases of dust-productive soils for atmospheric dust modelling (i.e. Nickovic et al. 2012).

## 7. TRANSITION TO OPERATIONAL ACTIVITIES: PROPOSED DESIGNATION AS REGIONAL SPECIALIZED METEOROLOGICAL CENTER WITH SPECIALIZATION ON ATMOSPHERIC SAND AND DUST FORECASTING (RSMC-ASDF)

Those institutions/nodes have reached a high level of maturity in dust forecasting and are interested and commit to initiate operational dust predictions in the context of the WMO Global Data-Processing and Forecasting System (GDPFS) and Regional Specialized Meteorological Centre (RSMC) structures, should follow the procedure, prepared by the WMO Commission for Basic Systems (CBS). The current procedure, suggested by CBS on 13 January 2015 and reviewed by relevant CBS experts and DPFS secretariats, is enclosed as Annex 2[c].

[c] *The Procedure can be further specified by the World Meteorological Organization (WMO) Commission for Basic Systems (CBS)*

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**ANNEX 1**

## Resolution 13 (EC-66)

## SAND AND DUST STORM WARNING ADVISORY AND ASSESSMENT SYSTEM

THE EXECUTIVE COUNCIL,

**Noting**:

(1) The three Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Regional Nodes for Asia, Pan America and for Northern Africa, Middle East and Europe,

(2) The additional potential Regional Node in West Asia in collaboration with the United Nations Environment Programme,

(3) The development of the SDS-WAS Science and Implementation Plan,

**Considering** the need for a global coordination mechanism to facilitate information exchange among these SDS-WAS Regional Nodes,

**Recommends**:

(1) That the SDS-WAS Steering Committee be established, with two nominations from each Regional Node;

(2) That once established, the Steering Committee will select a chairperson, on a rotational basis from its members, for a two-year period;

(3) That the Steering Committee will meet regularly to review research progress and priorities, and that the Chairperson of the Committee will report the SDS-WAS-related activities to annual meetings of the World Weather Research Programme Scientific Steering Committee;

(4) That the Steering Committee be funded by the SDS-WAS Trust Fund from contributing Members;

**Requests** the Secretary-General to support the establishment of the Steering Committee and the Trust Fund for the Sand and Dust Storm Warning Advisory and Assessment System.

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**ANNEX 2**

## Designation Process of RSMC ASDF to be included in SDS-WAS Implementation Plan

Transition to operational activities: Standard designation procedure as Regional Specialized Meteorological Centre with activity specialization in Atmospheric Sand and Dust Forecasting (RSMC-ASDF)

An institution can be designated as Regional Specialized Meteorological Centre with activity specialization in Atmospheric Sand and Dust Forecasting (RSMC-ASDF) if its regional node has reached a high level of maturity in dust forecasting and it is also capable of producing operational dust predictions in real time 24 hours a day, 7 days a week and 365 days a year. The mandatory functions of RSMC-ASDF are described in the Manual on the Global Data Processing and Forecasting System (GDPFS) (WMO-No. 485). If a group of institutions share the RSMC functions, they can be designated as RSMC Network with activity specialization in ASDF. Such institution(s) concerned shall go through the following designation procedures:

step 1. The institution concerned should express its intent to be designated as RSMC-ASDF to the SDS-WAS Regional Steering Group (RSG) of its regional node and shall prepare a technical report to outline the institution's operational capabilities as well as to demonstrate the quality of dust forecasts for operational use in the region following criteria and recommendations documented in the GDPFS Manual (WMO-No. 485). Model evaluation and inter-comparison studies by the SDS-WAS regional node shall be described in detail. The proposal, including the technical report, requires the approval by the SDS-WAS RSG.

step 2. The institution concerned should express its intent to be designated as RSMC-ASDF to the President of the Regional Association (P/RA) through, and with the endorsement of, Permanent Representative (PR) of the country in which it is situated to ensure commitment to provide the information as described in the Manual on GDPFS and shall obtain the approval of P/RA on this designation proposal.

step 3. The Chair of the SDS-WAS RSG should convey the intent of the institution concerned to SDS-WAS Steering Committee (SC) with the technical report. The SDS-WAS SC shall review the proposal, including the technical report. The proposal requires the approval by the SDS-WAS SC.

step 4. The Chair of the SDS-WAS SC should submit the technical report and propose the nomination of the institution concerned to the Scientific Steering Committee of World Weather Research Programme (WWRP SSC). The proposal requires the approval by WWRP SSC.

step 5. The Chair of WWRP SSC should submit the technical report and propose the nomination of the institution concerned to the President of the Commission of Atmospheric Science (CAS) (P/CAS). When P/CAS approves the proposal, P/CAS shall recommend the proposal, including the technical report, to the President of the Commission for Basic Systems (CBS) (P/CBS).

step 6. P/CBS shall request the Expert Team on Emergency Response Activity (ET-ERA) through the Chair of Open Programme Area Group on DPFS (OPAG-DPFS) to review the proposal and the technical report. The proposal, including the technical report, requires the approval by ET-ERA.

step 7. When the proposal of the institution concerned is approved by relevant experts of CAS and CBS, the institution will be invited by CBS to present the proposal (in the form of an amendment to the Manual on the GDPFS) at one of its sessions for decision. The presentation of the proposal shall be complemented by the respective demonstration of capabilities, through documentation as well as oral presentation. WMO Secretariat will assist in the development of the proposed amendment to the Manual on the GDPFS.

step 8. With the approval of the Members of CBS, the amendment to the Manual will be put up to WMO Congress or to WMO Executive Council for approval.

step 9. With this final WMO approval, the Manual on the GDPFS will be revised and the institution concerned will be formally designated as RSMC ASDF.

# World Weather Research Programme (WWRP) Report Series

Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI), San Jose, Costa Rica, 21-30 November 2006 (WMO TD No. 1383**) (WWRP 2007 - 1).**

Third WMO International Verification Workshop Emphasizing Training Aspects, ECMWF, Reading, UK, 29 January - 2 February 2007) (WMO TD No. 1391) **(WWRP 2007 - 2).**

WMO International Training Workshop on Tropical Cyclone Disaster Reduction (Guangzhou, China, 26 - 31 March 2007) (WMO TD No. 1392) **(WWRP 2007 - 3)**.

Report of the WMO/CAS Working Group on Tropical Meteorology Research (Guangzhou, China, 22-24 March 2007) (WMO TD No. 1393) **(WWRP 2007 - 4).**

Report of the First Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), (Geneva, Switzerland, 23-25 April 2007) (WMO TD No. 1412) **(WWRP 2007 - 5).**

Report of the CAS Working Group on Tropical Meteorology Research (Shenzhen, China, 12-16 December 2005) (WMO TD No. 1414) **(WWRP 2007 - 6).**

Preprints of Abstracts of Papers for the Fourth WMO International Workshop on Monsoons (IWM-IV) (Beijing, China, 20-25 October 2008) (WMO TD No. 1446) **(WWRP 2008 - 1).**

Proceedings of the Fourth WMO International Workshop on Monsoons (IWM-IV) (Beijing, China, 20-25 October 2008) (WMO TD No. 1447) **(WWRP 2008 - 2).**

WMO Training Workshop on Operational Monsoon Research and Forecast Issues – Lecture Notes, Beijing, China, 24-25 October 2008 (WMO TD No. 1453**) (WWRP 2008 - 3).**

Expert Meeting to Evaluate Skill of Tropical Cyclone Seasonal Forecasts (Boulder, Colorado, USA, 24-25 April 2008) (WMO TD No. 1455) **(WWRP 2008 - 4).**

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Strategic Plan for the Implementation of WMO's World Weather Research Programme (WWRP): 2009-2017 (WMO TD No. 1505) **(WWRP 2009 - 2).**

4th WMO International Verification Methods Workshop, Helsinki, Finland, 8-10 June 2009 (WMO TD No. 1540) **(WWRP 2010 - 1).**

1st WMO International Conference on Indian Ocean Tropical Cyclones and Climate Change, Muscat, Sultanate of Oman, 8-11 March 2009 (WMO TD No. 1541) **(WWRP 2010 - 2).**

Training Workshop on Tropical Cyclone Forecasting WMO Typhoon Landfall Forecast Demonstration Project, Shanghai, China, 24-28 May 2010 (WMO TD No. 1547) **(WWRP 2010 - 3)** (CD only).

2nd WMO International Workshop on Tropical Cyclone Landfall Processes (IWTCLP-II), Shanghai, China, 19-23 October 2009 (WMO TD No. 1548) **(WWRP 2010 - 4).**

5th WMO Symposium on Data Assimilation, Melbourne, Australia, 5-9 October 2009 (WMO TD No. 1549) **(WWRP 2010 - 5).**

7th International Workshop on Tropical Cyclones (IWTC-VII), Saint-Gilles-Les-Bains, La Réunion, France, 15-20 November 2010 **(WMO TD No. 1561) (WWRP 2011 - 1).**

Report of the Fourth Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 21-24 February 2011, **(WWRP 2011 - 2).**

WWRP/ETRP Workshop on Operational Monsoon Research and Forecast Issues – Lecture Notes, Beijing, China, 24-25 October 2008, **(WWRP 2011 - 3).**

Recommended Methods for Evaluating Cloud and Related Parameters **(WWRP 2012 - 1).**

Proceedings of the 10th WMO Scientific Conference on Weather Modification, Bali, Indonesia, 4-7 October 2011 **(WWRP 2012 - 2).**

Fifth Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 11-13 April 2012, **(WWRP 2012 - 3).**

**1.1** Second WMO/WWRP Monsoon Heavy Rainfall Workshop, Petaling Jaya, Malaysia, 10-12 December 2012 **(WWRP 2013 - 1).**

International Workshop on Unusual Behaviour of Tropical Cyclones, Haikou, Hainan, China, 5-9 November 2012, **(WWRP 2013 - 2).**

Abstracts of Papers for the Fifth WMO International Workshop on Monsoons (IWM-V), Macao, China, 28-31 October 2013, Hong Kong, China, 1 November 2013, **(WWRP 2013 - 3).**

Second International Conference on Indian Ocean Tropical Cyclones and Climate Change (IOTCCC-II), New Delhi, India, 14-17 February 2012 **(WWRP 2013 - 4).**

WMO/WWRP International Workshop on Rapid Changes in Tropical Cyclone Intensity and Track, Xiamen, China, 18-20 October 2011 (**WWRP 2013 - 5**).

5th International Verification Methods Workshop, Melbourne, Australia, 5-7 December 2011 (**WWRP 2013 - 6**).

Verification Methods for Tropical Cyclone Forecasts (**WWRP 2013 - 7**).

Sixth Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 18-19 July 2013 (**WWRP 2014 - 1**).

Joint Meeting of the THORPEX International Core Steering Committee (ICSC) and the World Weather Research Programme (WWRP) Joint Scientific Committee (JSC), (Geneva, Switzerland, 17 July 2013) (**WWRP 2014 - 2**).

Workshop on Communicating Risk and Uncertainty, Melbourne, Australia, 26-27 July 2012 (**WWRP 2014 - 3).**

International Conference on Opportunities and Challenges in Monsoon Prediction in a Changing Climate (Pune, India, 21-25 February 2012) (**WWRP 2014 - 4**).

Workshop on Operational Monsoon Research and Forecast Issues, Training Notes (Part A – IWM-V, Hong Kong, China, 1 November 2013, Part B – IWM-IV, Beijing, China, 24-25 October 2008) (**WWRP 2014 - 5**).

6th International Verification Methods Workshop, New Delhi, India, 13-19 March 2014 (**WWRP 2014 - 6**).

Pre-Workshop Topic Reports Eighth WMO International Workshop on Tropical Cyclones (IWTC-VIII) Jeju, Republic of Korea, 2-10 December 2014 (**WWRP 2014 - 7**).

Proceedings of the 5th International Workshop on Monsoons, Macao, China, 28-31 October 2013, Hong Kong, China, 1 November 2013 (**WWRP 2015 - 1**).

Seventh Session of the Scientific Steering Committee (SSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 18-20 November 2014 (**WWRP 2015 - 2**).

8th International Workshop on Tropical Cyclones (IWTC-VIII), Jeju, Republic of Korea. 2-6 & 10 December 2014 (**WWRP 2015 - 3**).

3rd International Workshop on Landfall Processes (IWTCLP-3), Jeju, Republic of Korea, 8-10 December 2014 (**WWRP 2015 - 4**).