

Chapter X : Numerical Prediction of Dust

A. Benedetti¹, J.M. Baldasano³, S. Basart³, F. Benincasa³, O. Boucher², M. Brooks¹¹, J.P. Chen¹², P.R. Colarco⁴, S. Gong¹⁴, N. Huneeus², L. Jones¹, S. Lu⁸, L. Menut², J.-J. Morcrette¹, J. Mulcahy¹¹, S. Nickovic⁷, C. Pérez¹³, J.S. Reid⁵, T.T. Sekiyama⁹, T. Tanaka⁹, E. Terradellas⁶, D.L. Westphal⁵, X.-Y. Zhang¹⁰, C.-H. Zhou¹⁰

¹European Centre for Medium-Range Weather Forecasts, Reading, UK; ²Laboratoire de Météorologie Dynamique, Paris, France; ³Barcelona Supercomputing Centre-CNS, Barcelona, Spain; ⁴NASA Goddard Space Flight Center, Maryland, USA; ⁵Naval Research Laboratory, Monterey, CA, USA; ⁶Spanish Meteorological Agency, AEMET, Barcelona, Spain; ⁷World Meteorological Organisation, Switzerland; ⁸National Centers for Environmental Prediction, Maryland, USA ; ⁹Japan Meteorological Agency/Meteorological Research Institute, Tsukuba, Japan; ¹⁰ Chinese Academy of Meteorological Sciences, Beijing, China; ¹¹UK Met Office, Exeter, UK; ¹²National Taiwan University, Taipei, Taiwan; ¹³NASA GISS, New York, USA, ¹⁴Environment Canada, Toronto, Canada

1. Introduction

1.1. Rationale for Dust Forecasting

As discussed throughout this book, airborne dust is a key atmospheric constituent. Emissions of dust in arid and semi-arid regions represent an important natural source of atmospheric particulate matter, which is considered to be a harmful air pollutant. Atmospheric dust causes respiratory diseases, infections and, in some regions, can also contribute to trigger serious epidemics, such as meningitis in the Sahel (Thomson et al. 2006). Dust also plays an important role in different aspects of weather and climate dynamics, the Earth's radiative budget, cloud microphysics and atmospheric chemistry. The radiative heating of airborne dust modifies the energetics of the atmosphere, including the possible modifications of easterly waves and tropical cyclone development (Karyampudi and Carlson, 1988; Karyampudi and Pierce, 2002). Dust interacts with continental and maritime ecosystems, by being a source of micronutrients (e.g. Okin, et al. 2004; Jickells et al., 2005; Schulz et al, 2012). It also modifies atmospheric energy budgets and the characteristics of surface radiation. Finally, on a daily basis significant dust events have a substantial economic impact as reduced visibility can affect air traffic, road transportation and military operations. Dust affects the semiconductor industry which requires a clean atmosphere to manufacture electronic chips. Reduced radiation at the surface has an impact on the output from solar power plants, especially those which rely on direct solar radiation (Schroedter-Homscheidt et al, 2012).

From ancient times the atmospheric dust process and dust storms were attracting the societal attention. In ancient Korea, dust events caused concern because they were considered as God's punishment or a warning to the ruler. Figure XX.1 shows a historical record on dust observation in Korea originating from the first century BC (Chun, et al. 2008). Two millenniums later, Darwin (1846) was the first who published a scientific record on intercontinental transport across the Atlantic Ocean originating from Sahara.

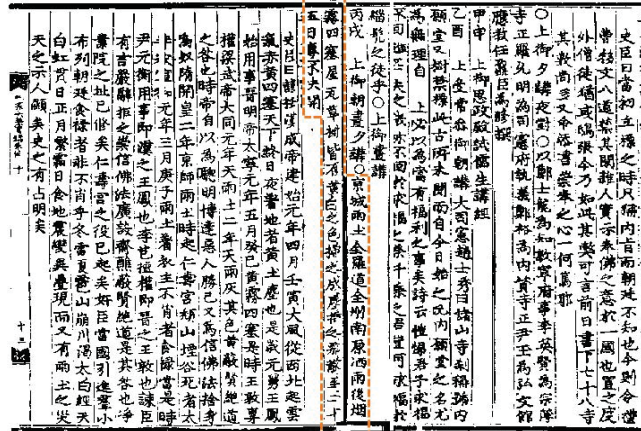


Fig. XX.1 An example of an ancient dust record on dust fallen on Seoul, Korea during the reign of King Myong-jong (SN: permission from AMS will be needed for this Fig, if we want to include it)

First ideas on numerical prediction of the atmospheric dust process were proposed by Richardson (1922) who added the atmospheric dust as one of eight variables in the first (although unsuccessful) numerical weather prediction system (Edwards, 2000). Decades later, Westphal et al. (1988) studied the importance of low-level nocturnal jets and the middle level easterly jet on dust mobilization and transport using the first multi-dimensional, size-resolving, full physics numerical model. This implementation demonstrated the practicality of numerical simulations of dust storms.

The scientific interest to study and predict the dust process enormously increased over past decades. The citation index in Figure XX.2 shows an exponential growth in the publication rate, starting from the early works of Prospero and Carlson in the 1970s (Kaufman et al., 2005). The exponential increase corresponds to doubling of the publication rate every 4 years, as compared to publication rate on climate change that doubles every 11 years (Stanhil, 2001).

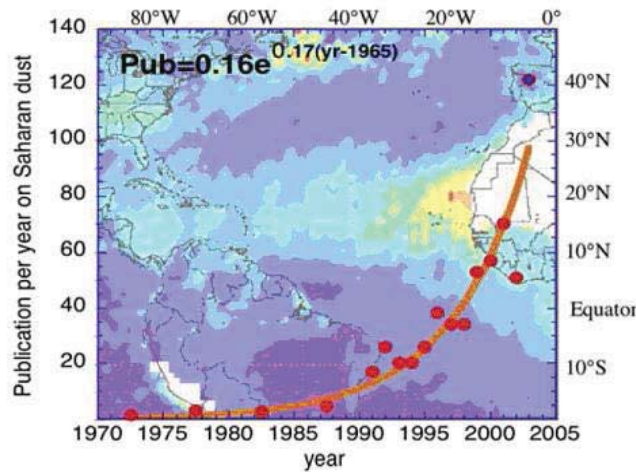


Figure XX.2 Exponential increase in publications on Saharan dust.

While the importance of airborne dust was well recognized, it is only in the past decade that development of operational forecasting capabilities for atmospheric aerosols in general and dust in particular has been intensified. Several reasons motivated the development of prototype, pre-operational and operational dust monitoring and forecast capability:

- 1) Decision makers have long desired the ability to nowcast and forecast severe dust events in order to mitigate dust's impact on such operational areas transportation, military operations, energy, and health. In some regions of the world, even the livelihood of people is threatened by dust storms which can be of extreme severity and can force the closing of roads and airports. Health advisories to susceptible populations require dust information as input. Solar systems require forecasts of solar insolation to help predict their contribution to the power grid.
- 2) Dust interacts with atmospheric radiation and can modify significantly the Earth's radiative budget. While the importance of dust-climate interactions has long been recognised, it is only recently that the importance of dust for weather forecasting itself was fully appreciated (Perez et al. 2006a). Haywood et al. (2005) showed that the Met Office numerical weather prediction (NWP) model had a bias of -35 Wm^{-2} in its top-of-atmosphere radiative budget over the Saharan region because it neglected the effects of dust on radiation. Such systematic biases in NWP models can be addressed by prescribing better aerosol climatologies (e.g., Tompkins et al., 2005) but interactive aerosols in NWP models are increasingly being exploited to improve the skill of weather forecasts. Indeed, major dust storms have been shown to feed back into their corresponding weather events (Wang et al., 2010). The impact of dust on tropical cyclone intensity is highly studied (e.g., Dunion and Velden, 2004; Evan et al., 2006).
- 3) Dust's infrared signature causes interference in IR retrievals and subsequent assimilation of temperature, humidity and sea surface temperature. For example, Weaver et al. (2003) show how TOVS temperature profiles can be contaminated by dust. Ruescas et al. (2011) demonstrated impact to SST retrievals which are used operationally as a boundary condition in models. Maddy et al. (2012) demonstrated significant dust impacts of up to 4 K on AIRS retrievals of the atmospheric temperature profile. Given the extreme loadings of some dust events from Africa and Asia, dust must be accounted for in models that utilize data assimilation based on infrared wavelengths.
- 4) There is a pressing need to monitor the Earth's environment to better understand changes and adapt to them, especially in the context of climate. This necessity provided the impetus for the Global Monitoring of the Environment and Security (GMES, now renamed as Copernicus) initiative in Europe. Monitoring does not necessarily require a forecasting capability. However, since the dust cycle is so much related to meteorological conditions, the benefit of combining the monitoring of the atmosphere with the monitoring of atmospheric species became clear very early in the planning of the GMES project. It was therefore a quite natural step to extend the capability of numerical weather prediction (NWP) models to chemical species (Hollingsworth et al., 2008).

Operational dust forecasting occurred progressively through a number of steps. The predecessor of the DREAM dust model (Nickovic, 1996; Nickovic and Dobricic, 1996) was

the first regional dust model developed in the period 1991-1993 in which dust concentration was built into the prognostic equations of the atmospheric model driver. This system was implemented at the Tunisian Meteorological Service and was successfully run on an experimental daily basis in the period March-May. First longer experimental dust forecasts were performed during 1996-1997 within the EU-funded project "MEDUSE" when the model was driven by the atmospheric SKIRON system (Nickovic et al, 1997).

To address military needs, the Navy Aerosol Analysis and Prediction System was modified by including dust, smoke and sea salt, thus allowing off-line predictions of aerosol concentration, extinction and visibility. It was run in a near real-time manner in 1998 and then became the first fully operational multi-species global aerosol forecast model in 2005. Since dust storms are a significant weather phenomenon in the Iraq region in winter and spring, Liu et al. (2007) modified the Coupled Ocean-Atmospheric Mesoscale Prediction System (COAMPS) to include an in-line dust aerosol model for use during Operation Iraqi Freedom (OIF) in March and April 2003. Verification showed that COAMPS predicted the arrival and retreat of the major dust events and predicted the intensity (reduction in visibility) of storms with an error of less than 1 km. The forecasts are still produced on an operational basis.

Quasi-operational and operational forecasts have since then become available from a number of NWP and research centres around the world (BSC-CNS, CMA, ECMWF, FNMOC, LMD, JMA, Met Office, NASA, NCEP, NRL, TEPA). Many of these forecasts are now delivered through the regional nodes of the WMO Sand and Dust Storm Warning Advisory and Assessment System programme (<http://www.wmo.int/sdswas>). Other forecasts are delivered through dedicated web interface or serve the purpose of the individual operational centres.

1.2 Specific challenges in dust prediction

Despite the prevalence and importance of airborne dust, the field of numerical prediction of dust faces a number of challenges of the system's observability and predictability. At the centre of the problem are the vast dimensions of scale required to fully account for all of the physical processes related to dust. Prediction of dust is fundamentally a mechanical/dynamical problem and dust production is essentially a function of surface wind stress and soil conditions. In both cases, there is a significant influence on surface property and meteorological scales. Consider that wind alone can range from synoptic generation (e.g., Westphal et al., 1988), to mesoscale phenomena such as produced by mountain passes (Liu and Westphal, 2001), or thunderstorm downdrafts/convective cold pools (or Haboobs) (Knippertz et al., 2007; Miller et al., 2008). Micro-scale phenomenon such as mixing in the boundary layer the nocturnal jet (Abdou et al., 2007; Knippertz and Todd, 2010) and gustiness are also important (Engelstaedter and Washington 2007). In addition to the baseline meteorology, one must consider the complexity of the soil properties and emissions physics. While emissions models range from the simple to the highly complex, it is universally agreed that emissions are strongly nonlinear in such factors as the momentum flux, soil moisture, mineralogy and the availability of saltators to name a few (e.g., see Gillette (1978) to Kok et al., (2012) for a synopsis of the evolution of the field). Regardless, very often in global models the functional form of emission in that of a power law, making emissions highly sensitive to modelled wind fields. In addition to bulk emissions, size dependent emissions and transport are also complex. While the average size of common mode dust particles which undergo long range transport is surprisingly static (Dubovik et al., 2002; Maring et al., 2003; Reid et al., 2003; 2008), with a volume median diameter of $\sim 4-7 \mu\text{m}$, short lived giant mode

particles (15-100 μm particles) are an important but largely unstudied component of dust. Modelling the transport and sink of large particles requires attention to similar non-linear processes as the sources.

The sensitivity of dust emissions to the environment has led to long recognition of the sensitivity of dust simulations to model resolution (Liu and Westphal, 2001; Reinfried et al., 2009; Gläser, et al., 2012; Takemi, 2012). The quality of the model winds is dictated by the model characteristics such as horizontal resolution and numerical solver, and it is also limited by the relatively low amount of wind observations available for the analysis. Moreover, many large-scale models and regional models do not have the capability to resolve convective-scale phenomena such as haboobs or dust devils (e.g. Knippertz et al., 2009), and are therefore missing potentially important emission sources. A good dust forecast is then driven by the accuracy of the surface winds in the model, the type of parameterizations used to describe emission and removal processes, the accuracy of the transport scheme, and the quality of the atmospheric fields that interact with dust particles (for example, cloudiness and precipitation for wet deposition). Nevertheless, a certain degree of accuracy in the prediction of dust at the synoptic scale and in some cases at the regional scale has been achieved in the last few years, to the point that the information from the prediction models can be offered to forecasters as guidance.

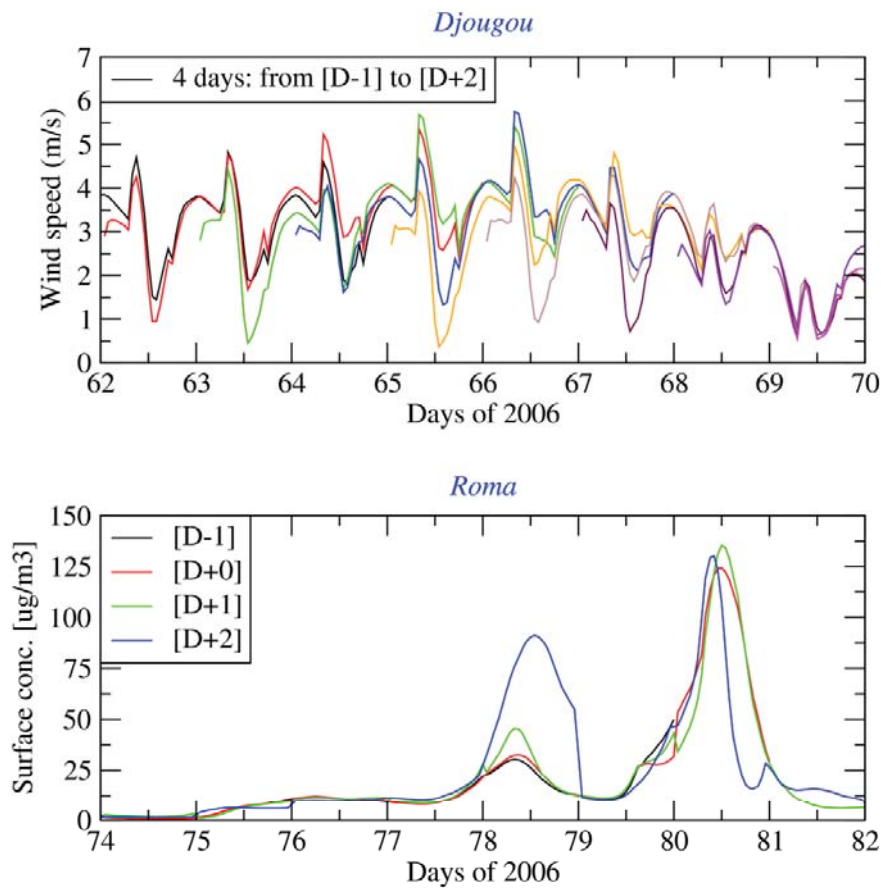


Figure XX.3 Time series of modelled wind speed (top) and dust surface concentrations (bottom).

The issue of dust predictability is illustrated with an example in Figure XX.3 which presents time series of modelled wind speed and dust surface concentrations. For the wind speed, here presented for the Djougou site and modelled with WRF (Menut et al., 2009), each coloured line represents a forecast of five days. The corresponding days are superimposed and show the spread from one forecast to the following. The wind speed values are ranging between 1 to 6m/s and the differences between each forecast lead is not exceeding 1m/s. From a meteorological point of view, this variability is not important. However, it becomes important when this modelled wind speed is used for dust emissions and transport. After long-range transport from Africa to Europe, the dust concentrations modelled with CHIMERE are presented the same figure over Roma (Italy). The variability in the dust surface concentrations at the various forecast ranges appears very large. Variations in dust can be of the same order of magnitude as the maximum concentrations of aerosols regulated by air quality policies.

Compounding issues surrounding the predictability of dust emissions and transport are similar challenges in dust observability. Both satellite and ground based observations are needed for nowcasting, data assimilation, and evaluation tools. From satellite, a host of dust enhancement products is available to identify major dust features (e.g., TOMS/OMI UV Aerosol Index: Herman et al., 1997; MODIS enhancement product: Miller, 2003; SEVIRI RGB product: Lensky and Rosenfeld, 2008, are all commonly used operationally). However these are qualitative in nature and as such cannot be readily used for assimilation in models. More quantitatively, Aerosol Optical Depth (AOD) retrievals are commonly available over water and can be assimilated with correction (e.g., Zhang and Reid 2006). Over bright desert surfaces where there is reduced differences between the aerosol signal to surface, perturbations on previous dark target methods such as the Deep Blue algorithm (Hsu et al., 2004), or multi- angle viewing such as with MISR (Martonchick et al., 2004) is required. But even in these circumstances, large errors exist which can prohibit assimilation, and for the largest events, AODs are so high that the retrievals fail. This leaves models without reliable data for assimilation near source regions. Further, while AOD is a common model benchmark, functionally models carry mass, and there is virtually no reliable or representative datasets for mass evaluation in major dust source regions. The little data available tends to come from short field missions.

In recent years, a new pathway has been chosen to alleviate the shortcomings of any individual model through the development of a multi-model ensemble forecasting framework. Regional and global multi-model ensembles for dust prediction have been established to offer better information and products to the users. These will be discussed in Section 3. In the next section, a description of the operational and quasi-operational dust prediction models contributing to this multi-model ensemble effort is offered. Section 4 discusses briefly the characteristics of the dust prediction systems with assimilation capabilities. Section 5 presents an overview of the type of verification and evaluation procedures these systems are subject to. Finally, Section 6 presents a summary and a future outlook on dust prediction activities.

2. Dust Prediction Models

This section summarises the characteristics of some of the current aerosol prediction models that are run in an operational or quasi-operational manner at various centres around the world. This compilation is not intended to be exhaustive, but is meant to provide a sample of models. In an effort to be as inclusive as possible, both global and regional systems are

briefly described. Further information regarding the model characteristics such as horizontal and vertical resolution, and dust emission and deposition parameterizations in the various models is provided in Table 1 and Table 2. References are also provided for further reading on any specific model.

2.1 Global models

2.1.1 ECMWF/MACC aerosol prediction model

Since 2008 ECMWF has been providing aerosol forecasts including dust as part of the EU-funded projects GEMS, MACC and MACC-II (available online at www.gems-atmosphere.eu). A detailed description of the ECMWF forecast and analysis model including aerosol processes is given in Morcrette et al. (2009) and Benedetti et al. (2009). The initial package of ECMWF physical parametrisations dedicated to aerosol processes mainly follows the aerosol treatment in the LOA/LMD-Z model (Boucher et al., 2002; Reddy et al., 2005). Five types of tropospheric aerosols are considered: sea salt, dust, organic and black carbon, and sulphate aerosols. A bin representation is used to include prognostic aerosols of natural origin, such as mineral dust. The maximum flexibility regarding the limits of the bins for dust aerosols is allowed in the model. In the current version of the model, the desert dust aerosols are represented by 3 bins with radius limits at 0.03, 0.55, 0.9, and 20 μm . Emissions of dust are parameterised following an approach modified from Ginoux et al. (2001) and depend on the 10-m wind, soil moisture, the UV-visible component of the surface albedo, and the fraction of land covered by vegetation when the surface is snow-free. A correction to the 10-m wind to account for gustiness is also included (Morcrette et al, 2008).

2.1.2 FNMOC Navy Aerosol Analysis and Prediction System

The US Navy has invested in aerosol and dust forecasting since the mid-1990s through the development of the Navy Aerosol Analysis and Prediction System (NAAPS). NAAPS has been forecasting quasi-operationally at the Naval Research Laboratory (NRL) since 1999, and became the first fully operational aerosol model through transition to the Fleet Numerical Meteorological and Oceanography Center (FNMOC) in 2007 making 6 day forecasts twice daily. Based on the Danish Eulerian Hemispheric Model (Christensen, 1997; Westphal et al., 2009), NAAPS is an offline chemical transport model currently running with single bin dust, smoke, sulfate, and sea salt at 1×1 degrees/ 27 levels driven by the 0.5 degree Navy Operational Global Analysis and Prediction System (NOGAPS; Hogan and Rosmond, 1991). NAAPS has operational MODIS data assimilation via a 2D-Var framework (Zhang et al., 2008), with 3D-Var and EnKF systems in development (e.g, Zhang et al., 2011). Next generation models such as an ensemble version of NAAPS run from the ensemble NOGAPS forecast is run quasi-operationally at NRL. Dust emission in NAAPS is based on modelled friction velocity to the forth power coupled to an erodability map multiplier. Operationally this map was empirically derived from TOMS AI products. A transition is in place to adopt the recently expanded 1 km high resolution database of Walker et al. (2009). Data products with verification tools can be found at <http://www.nrlmry.navy.mil/aerosol/> with archives at <http://www.usgodae.org/>.

2.1.3 JMA operational dust forecast model

Japan Meteorological Agency (JMA) has been providing the “Aeolian Dust Information” to the general public via its website (<http://www.jma.go.jp/en/kosa/>) since January 2004. The operational numerical dust forecast in JMA is based on a global aerosol model called Model of Aerosol Species in the Global Atmosphere (MASINGAR) (Tanaka et al., 2003), which is coupled with MRI/JMA98 AGCM. Dust particles are logarithmically divided into 10 discrete size-bins from 0.1 to 10 μm in radius. The operational version of MASINGAR calculates the emission flux of dust as a function of the third-power of 10-m wind velocity (Gillette, 1978), soil moisture, soil type, snow cover, and vegetation cover. A threshold 10-m wind velocity is set to 6.5 m s^{-1} according to Tegen and Fung (1994). Snow cover by JMA surface analysis and monthly mean MODIS-retrieved leaf area index are used to constrain the erodible surface. The transport of dust is calculated with three-dimensional semi-Lagrangian advection, subgrid vertical diffusion, and moist convective transport, and gravitational settling. Removal processes of dust include rainout, washout, and dry deposition. JMA is planning to update the operational dust forecast model to another that is based on the latest global climate model MRI-CGCM3 (Yukimoto et al., 2012).

2.1.4 Met Office dust prediction system

The publicly available dust forecasts from the U.K. Met Office are produced by the Met Office’s global Numerical Weather Prediction (NWP) system. The dust scheme is essentially that of Woodward (2001) with modifications as described in Woodward (2011) and Collins et al. (2011). The dust emission scheme is based on Marticorena and Bergametti (1995) and represents an initial horizontal/saltation flux in a number of size bins with subsequent vertical flux of bare soil particles from the surface into the atmosphere. The global NWP model uses only 2 bins (0.1-2 microns and 2-10 microns) from the original 9 bins. The magnitude of the emission is a cubic function of the exceedance of the friction velocity over bare soil with respect to a threshold value, where this friction velocity is determined from the model wind field and boundary layer structure. The conversion from the horizontal flux to the vertical flux is first limited using the clay fraction in the soil texture dataset, according to Gillette (1979), and then partitioned into the new bins by prescribing the emitted size distribution. Once the dust is lifted into the atmosphere it is transported as a set of tracers by the model 3D wind field. Johnson et al. (2011) gives in-depth description and evaluation of the Met Office dust forecasts, in a local area model over North Africa.

2.1.5 NASA GEOS-5 Aerosol Forecasting System

The Goddard Earth Observing System (GEOS-5, Rienecker et al. 2008) is an Earth system model maintained at the NASA Global Modeling and Assimilation Office (GMAO) to support NASA mission needs and climate studies. GEOS-5 contains components for atmospheric circulation and composition, oceanic circulation and biogeochemistry, and land surface processes, and includes sophisticated modules for atmospheric and constituent data assimilation. Aerosols are carried online and radiatively coupled to the GEOS-5 AGCM using a version of the Goddard Chemistry, Aerosol, Radiation, and Transport module (GOCART, Chin et al. 2002). GOCART treats the sources, sinks, transport, and optical properties of dust, sea salt, black and organic carbon, and sulphate. For dust, GOCART employs a topographic source function and mobilization scheme based on Ginoux et al. (2001), and uses the wind speed threshold for dust emissions from Marticorena et al. (1997). The dust particle size distribution is discretized into five bins spanning radius range 0.1 – 10 microns. Further description of aerosol module, its implementation in the GEOS modelling system, and its performance is provided in Colarco et al. (2010). The current version of the

GEOS-5 forecasting system performs twice daily 5-day forecasts in a quasi-operational framework.

2.1.6 NCEP/NGAC global aerosol forecasting system

Since September 2012 NOAA NCEP begins to provide 5-day global dust forecasts once per day (at 00 UTC cycle) from NEMS GFS Aerosol Component (NGAC) system. The forecast model component is the Global Forecast System (GFS) within the NOAA Environmental Modeling System (NEMS) and the aerosol component is the Goddard Chemistry Aerosol Radiation and Transport Model (GOCART). Dust aerosols are represented by 5 bins with radius limits at 1, 1.8, 3, 6, and 10 micron. Dust emissions are parameterized following Ginoux et al. (2001). Removal processes include wet removal (scavenging and rainout) and dry deposition (gravitational sedimentation and surface uptake). The development of NGAC is part of NCEP's modeling efforts toward a unified modeling framework. The GOCART parameterizations, developed and implemented within GMAO's GEOS-5 earth system model (Colarco et al., 2010), were coupled with NCEP's NEMS GFS to establish the first interactive atmospheric aerosol forecasting system at NCEP (Lu et al., 2010, 2013). While the ultimate goal at NCEP is a full-up earth system with the inclusion of aerosol-radiation feedback and aerosol-cloud interaction, the current operational configuration is to maintain a low-resolution forecast-only system for aerosol prediction and a high-resolution forecasting and analysis system for medium range weather prediction.

2.1.7 NMMB/BSC-Dust model

The NMMB/BSC-Dust (Pérez et al., 2011) is the global and regional dust forecast operational system developed and maintained in the Barcelona Supercomputing Center–Centro Nacional de Supercomputación (BSC-CNS). This is an online multi-scale atmospheric dust model designed and developed at BSC-CNS in collaboration with NOAA/National Centers for Environmental Prediction (NCEP), NASA Goddard Institute for Space Studies and the International Research Institute for Climate and Society (IRI). The dust model is fully embedded into the Non-hydrostatic Multiscale Model NMMB developed at NCEP (Janjic et al., 2011, and references therein) and is intended to provide short to medium-range dust forecasts for both regional and global domains. The NMMB/BSC-Dust model includes a physically-based dust emission scheme which explicitly takes account saltation and sandblasting processes (White, 1979; Marticorena and Bergametti, 1995; Marticorena et al., 1997) and assumes a viscous sublayer between the smooth desert surface and the lowest model layer (Janjic, 1994; Nickovic et al., 2001). 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). It includes an 8-bins size distribution within the 0.1–10 μm radius range according to Tegen and Lacis (1996) and radiative interactions (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). These developments represent the first step towards a unified multiscale chemical-weather prediction system at BSC-CNS (NMMB/BSC-CTM; Jorba et al., 2012).

2.2 Regional models

2.2.1 The DREAM/BSC-DREAM8b models

The Dust Regional Atmospheric Model (DREAM; Nickovic et al., 2001) is based on the Euler-type partial differential nonlinear equation for dust mass continuity and is driven by NCEP/Eta. The model was developed at the Euro-Mediterranean Centre of Insular Coastal Dynamics (ICoD). In May 2005, the operational version of DREAM was transferred to the Environmental Modelling Laboratory of the Technical University of Catalonia (UPC) led by professor Baldasano and in September 2006 to Barcelona Supercomputer Center–Centro Nacional de Supercomputación (BSC-CNS). A set of updates during 2002–2005 (Nickovic 2002; Nickovic 2003; Nickovic et al., 2004; Nickovic 2005) included a source function based on the 1 km USGS land use data; 8 particle size bins within the 0.1 – 10 μm radius range according to Tegen and Lacis (1996), and in cooperation with the Oceanographic Institute (Erdemli, Turkey) an initial version of the dust-radiation feedback scheme. These developments were included in the BSC-DREAM8b model (Pérez et al., 2006a,b).

The BSC-DREAM8b v2 model (Pérez et al. 2006a,b; Basart et al., 2012a; <http://www.bsc.es/projects/earthscience/BSC-DREAM/>) includes a dust production scheme (Shao et al. 1993) with introduced viscous sub-layer (Janjic, 1994). Its source function is calculated using the USGS land use data and a topographic preferential source mask from Ginoux et al. (2001). Further, the model has implemented radiative feedbacks on meteorology (Pérez et al., 2006a) and an updated dry deposition scheme based on Zhang et al. (2001). In the last years, the operational versions of the model have been used for dust forecasting and as dust research tools in North Africa and southern Europe (e.g. Jiménez-Guerrero et al., 2008; Amiridis et al., 2009; Klein et al., 2010; Pay et al., 2010; Alonso-Pérez et al., 2011; Kokkalis et al., 2012). The model has also been evaluated and tested over longer time periods over Europe (e.g. Basart et al., 2012b; Pay et al., 2012) and against measurements at source regions (SAMUM I; Haustein et al., 2009 and BoDEx; Todd et al., 2008). Moreover, the model is NRT evaluated with satellites (MODIS and MSG) and AERONET data.

Recently, a 8-bin DREAM version, called DREAM8-NMME-MACC, driven by the NCEP/NMME non-hydrostatic model (Janjic 2001) has been developed, which includes assimilation of the MODIS satellite AOD (Pejanovic et al., 2010; Nickovic et al., 2012) and provides daily dust forecasts on South East European Virtual Climate Change Center (SEEVCCC; <http://www.seevccc.rs/>).

2.2.2 CHIMERE model

The CHIMERE model is dedicated to the transport and chemistry of numerous gaseous and aerosols species. CHIMERE has been in development for more than fifteen years and is intended to be a modular framework available for community use. The dust emission fluxes are calculated using the parameterization of Marticorena and Bergametti (1995) for saltation and the dust production model (DPM) proposed by Alfaro and Gomes (2001) for sandblasting. A complete description of the dust calculation is presented in Menut et al (2007). For long-range transport simulations, the modelled domain is very large and must include at the same time Africa (for emissions) and Europe (for the long-range transport and deposition). This leads to a coarse horizontal resolution of 1x1 degrees in many studies. In order to take into account the subgrid scale variability of observed winds, the dust emissions are thus estimated using a Weibull distribution for the wind speed (Menut, 2008).

In Menut et al (2009), an intensive observation period of the AMMA program was modelled in forecast mode to study the variability of the predictability of modelled surface dust concentrations. It was shown that the sum of all model uncertainties (emissions, transport, deposition) and of the spread of the forecasted meteorology induces variability in surface concentrations still higher than the required precision for European air quality forecast.

2.2.3 CUACE/Dust

CUACE/Dust is an integrated atmospheric chemistry modelling system applied for dust (see eight papers in a special issue at ACP: http://www.atmos-chem-phys.net/special_issue81.html), which has been operationally run for dust forecasts in CMA since 2004 and for the WMO SDS-WAS Asia Node-Regional Centre since 2007. CUACE has been designed as a unified chemistry module to be easily coupled onto any atmospheric models through a common interface and its aerosol module utilizes a size-segregated multi-component algorithm for different types of aerosols including dust, sea salt, black and organic carbon, nitrate and sulfate (Gong et al., 2003a; Zhou et al., 2012; Zhou et al., 2008). An dust emission schemes have been built in CUACE/Dust based on Marticorena and Bergametti (1995), Alfaro et al. (1997), and Alfaro and Gomes (2001). A detailed desert distribution with soil texture data base and dust particle-size distributions measurements from nine major deserts for China were adopted (Gong et al., 2003b; Zhang et al., 2003). One of the unique features of the CUACE/Dust is the implementation of a 3D-VAR data assimilation system operationally using both satellite and surface observations in near real time (NRT) to improve the initial conditions and hence the forecast results (Niu et al., 2008). A threat scoring system has been also developed where observations from various sources concerning dust aerosol, i.e. surface regular weather phenomenon of a SDS and satellite retrieved IDDI (Hu et al., 2008) in Asia, are integrated into a Geographic Information System (Wang et al., 2008).

2.2.4 FNMOC Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS)

NRL has developed an inline, multi-bin dust module inside the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS), simulating the evolution of the spatial and size distributions of mineral dust particles and passive volcano ash. Beginning with operational transition to FNMOC in 2003 for Operation Iraqi Freedom (Liu et al., 2001; 2007), COAMPS dust simulations are now run on multiple domains over the world daily, with forecasts out to 3 days at resolutions of up to 1 km. A 5th-order positive-definite flux-form advection scheme is used in both the horizontal and the vertical along with a semi-implicit mixing scheme of turbulent kinetic energy closure to achieve mass conservation with minimal dispersion. The aerosol physical processes of sedimentation, dry deposition, and wet removal are calculated using the dynamics and cloud fields of COAMPS. The dust source is based on the 1-km high-resolution dust source database of Walker et al. (2009) that has been developed based on empirical relationships between satellite observed dust and static land cover information.

2.2.4 Regional mineral dust forecast model in Taiwan

Taiwan's Environment Protection Administration (TEPA) has conducted East Asian dust storm forecasts since 2002 in collaboration with the Department of Atmospheric Sciences, National Taiwan University (NTU). They incorporated the dust deflation module of Wang et al. (2000) into the Taiwan Air Quality Model (TAQM) in 2002 and into the CMAQ model in 2010. Some of the model details can be found in Chen et al. (2004) and Table 1. The dust coupled TAQM (or TAQM-KOSA) is run twice a day for 57 and 81 km horizontal resolutions, each providing a 5-day forecast. TAQM-KOSA has also been used as a research tool to study dust effects on cloud microphysics and marine phytoplankton bloom by the NTU group. It was also modified to study local dust produced from dry river beds and agriculture lands with 3 km horizontal resolution. The simulations showed that dust from

river beds may raise local/regional PM concentration up to several hundred $\mu\text{g}/\text{m}^3$, and more dust is originated from these local sources than from long-range transport due to Taiwan's far distance from the major deserts. Local dust daily forecast has been included in routine operation since 2010. The dust scheme is being improved and incorporated into WRF and WRF-CHEM models, and coupled with the cloud microphysical scheme to provide better calculation of in-cloud and below-cloud scavenging of dust as well as dust radiation feedback. These versions will be gradually incorporated into daily operation after extensive tests.

3. Special topic: multi-model ensembles (ICAP/WMO SDS-WAS)

Stochastic or ensemble prediction is a form of Monte-Carlo analysis aimed to describe the future state of the atmosphere from a probabilistic point of view. Multiple simulations are run to account either for the uncertainty of the initial state or for the inaccuracy of the model and the mathematical methods used to solve its equations. In particular, multi-model forecasting intends to alleviate the shortcomings of any individual model through the combined use of several of them.

3.1 The International Cooperative for Aerosol Prediction multi-model ensemble

As a result of the maturity of an international community of global aerosol forecast model developers (Reid et al., 2011; Benedetti et al., 2011), the creation of broadly acceptable norms, benchmarks and scorecards to evaluate aerosol forecast skill became important issue. At the same time, the NWP community as a whole recognizes the value in multi-model ensembles in developing probabilistic forecast tools. Similarly, ensembles of global aerosol analyses are becoming an important tool for climate studies (Huneus et al., 2011). In response to community needs and views, member developers of the International Cooperative for Aerosol Prediction (ICAP) created a developmental global multi-model ensemble (MME) to allow exploration of relative differences between models and devise tools for probabilistic prediction. Current models in the ICAP-MME dust component include: 1) BSC NMMB; 2) ECMWF MACC; 3) JMA MASINGAR; 4) NASA GEOS-5; 5) NOAA NGAC 6) NRL developmental NAAPS; 7) NRL 20 member ensemble mean E-NAAPS. To allow for the inclusion of quasi-operational models, the ICAP-MME is run 24 hours behind operations times. Daily products include a host of mean-spread plots, threat scores, and verification plots. While currently ICAP-MME data is only available to participating member centres, it is expected to be made public on a quasi-operational basis in 2013.

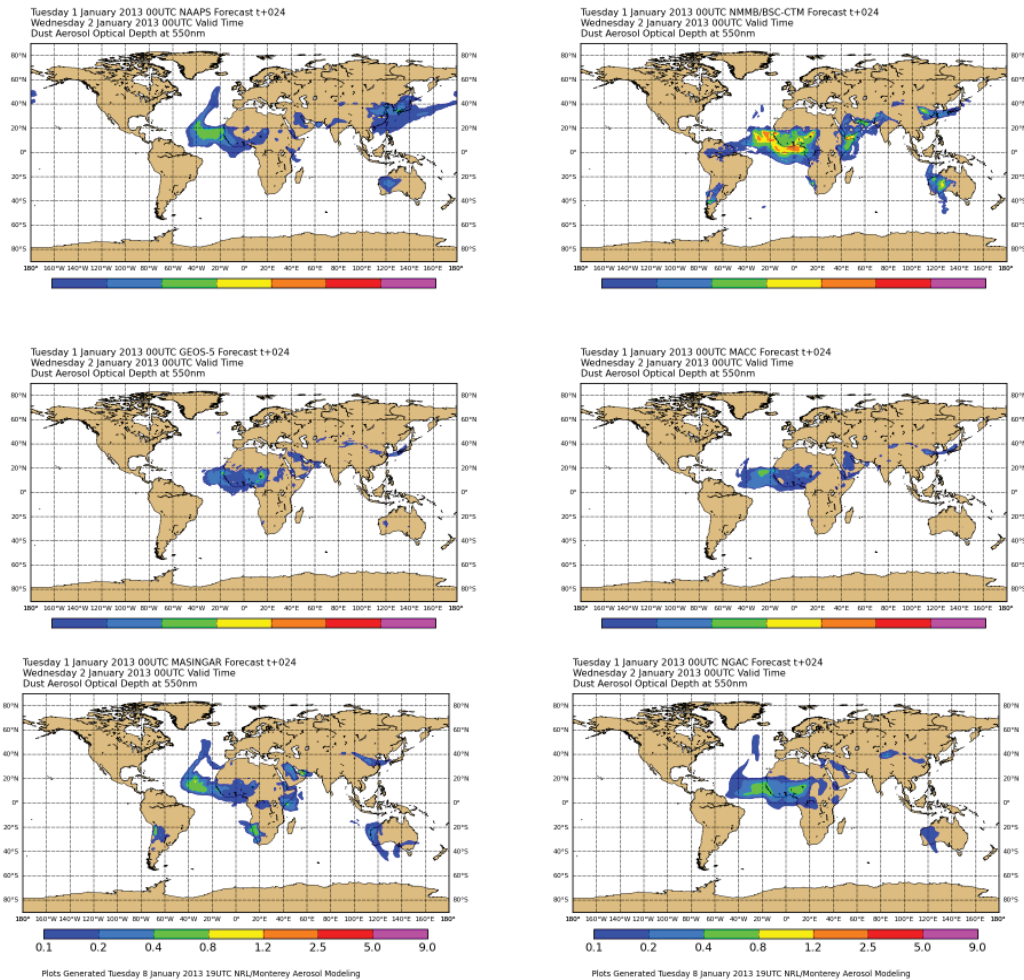


Fig. XX.4 Example of ICAP multi-model dust forecasts of aerosol optical depth at 550 nm for January 1, 2013.

3.2 WMO SDS Regional dust prediction multi-model ensemble

The WMO SDS-WAS Regional Centre for Northern Africa, Middle East and Europe (NA-ME-E) daily generates multi-model products for its region of interest (see Figure XX.6) from output files of different models (BSC-DREAM8b v2, MACC, DREAM8-NMME-MACC, CHIMERE, NMMB/BSC-Dust, MetUM, GEOS-5 and NGAC). Two products describing centrality (multi-model median and mean) and two products describing spread (standard deviation and range of variation) are calculated and daily available at <http://sds-was.aemet.es/>. In order to generate them, the model outputs are bi-linearly interpolated to a common grid mesh of 0.5° x 0.5°. The daily SDS-WAS NA-ME-E multi-model median (together with the individual models) is continuously evaluated against AERONET observations.

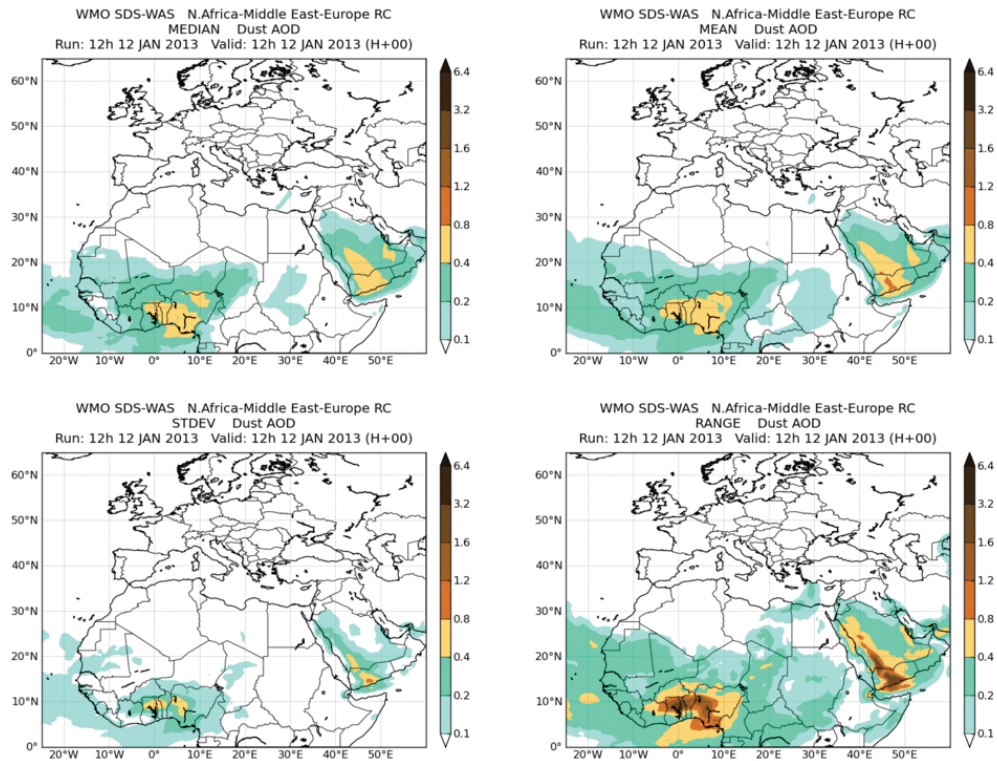


Fig. XX.5 Example of multi-model products issued by the WMO SDS-WAS Regional Center NA-ME-E: dust optical depth at 550 nm forecast for January 12, 2013. The plot shows two products describing centrality (multi-model median and mean) on the top panels and two products describing spread (standard deviation and range of variation) on the bottom panels.

4. Aerosol analyses for dust prediction

Some of the operational systems described in the previous section also run analysis suites to initialize the subsequent forecast. In some cases, the forecast models take the dust analysis from other systems to initialize the dust forecast. Assimilation of aerosol observations is still in its infancy, due to the complexity of the problem and the limited availability of aerosol observations in near real time. Due to the challenges of using aerosol-affected radiances from the visible channels of the current generation of imagers, most centres assimilate retrieval products (for example AOD) rather than the raw observations, with the exception of NASA GMAO where visible reflectances from satellite are used. Assimilation to improve dust prediction presents many challenges also due to the fact that AOD observations from sensors with visible channels are not available over bright surfaces. This is for example the case for the standard AOD data from the MODIS sensor on board of the Terra and Aqua satellites, which represent the most important source of NRT information for the systems with assimilation capabilities. MODIS data with different processing are used by ECMWF, NRL and NASA in their analysis. This implies that in current dust analysis, no information on dust is available over the sources, and any information is indirectly deduced from data in other regions, for example over the Atlantic Ocean where the dust outflow from the Sahara is the main contributor to the aerosol load. When relying on the assimilation to provide information on regions which are not observed, the model play a large role in extracting the information. Recently, there has been an ongoing effort at several centres to include other observations, for

example the land AOD product from the SEVIRI instrument on board of the MSG payload at the Met Office, MODIS Deep Blue at NRL, OMI data at NASA, and lidar backscatter at ECMWF, NRL, JMA. JMA/MRI has been pioneering the possibility of assimilating lidar data, with proven benefits on the dust prediction with their off-line assimilation and forecasting system (Sekiyama et al., 2010; Sekiyama et al., 2011).

4.1 What is data assimilation?

Data assimilation is the process to find the most likely estimation of the true system state via the combination of observations and model simulations. In other words, data assimilation is an objective way of filling-in information gaps and finding the optimal estimate. One of the simplest rules of the informational combination is the least-squares method, which is a weighted-mean calculation based on Bayesian estimation. No matter how complicated the schemes and systems are involved, the basic concepts of data assimilation are always similar to this weighted-mean calculation.

Most of the current dust prediction systems rely on the developments which are in place for the meteorological models: for example, ECMWF uses the incremental 4D-Var formulation with augmented control vector to include an aerosol total mixing ratio variable (Benedetti et al. 2009). At the UK Met Office 4D-Var assimilation of dust observations follows Benedetti et al. (2009) using total dust concentration as the analysis control variable. In the case of the regional NMME-DREAM8 dust model (Pejanovic et al., 2010), an assimilation method based on the Newtonian relaxation is applied using background dust concentration of the DREAM dust model and target fields of ECMWF dust analysis in dust initial field that includes the MODIS aerosol objective analysis. Some of these techniques and the solutions adopted at the various centres are briefly described below, highlighting especially the challenges that aerosol assimilation poses, as well as the benefits of the analysis for the dust prediction.

It is important to remember that most of the aerosol analysis systems currently employed operationally, solve an initial condition problem, meaning that the analysis is used to obtain the initial conditions in the aerosol fields so that the subsequent forecast matches the observations in the most optimal way, according to the specified background and observation errors. In most cases, this type of analysis is not sufficient. For example, in the case of point source such as volcanoes, an initial condition analysis is not sufficient and one would need to implement an emission estimate to really benefit from the observations. Studies which include estimation of emissions have been shown promising both for dust (Sekiyama et al. 2011) and other aerosol types (Huneeus et al., 2012), and it is likely that future aerosol analysis systems will include also emission parameters in their control variables. The other aspect which is peculiar to aerosol assimilation is that the problem is severely under-constrained due to the fact that several aerosol species have to be constrained with a total column-integrated observation for radiometric measurements or a profile of backscattering for lidar measurements. This implies that there is not a one-to-one correspondence between the observations and the variable to be optimized (control variable). The main differences between the various approaches (variational, ensemble Kalman filter, etc) boil down to getting around this problem, with a series of “clever” assumptions. For example, ECMWF formulates the control variable in terms of a total aerosol mixing ratio and distributes the increments from this variable into the single species mixing ratios in order to avoid defining the error statistics for all species, which would be too heavily reliant on the model. Other centres, for example MRI/JMA, use the state vector augmentation method where the emission

intensity is treated as a poorly known model parameter, which is defined at each model surface grid point. The control vector then consists of the dust emission parameters and model variables such as aerosol concentrations and meteorological components.

In the end, it has to be accepted that no matter how complex and sophisticated the aerosol assimilation system is, it should be clear that a lot of the information comes from the *model* rather than the *observations*.

4.2 Brief overview of assimilation techniques

4.2.1 Variational methods (ECMWF, FNMOC/NRL, Met Office, NASA GMAO)

The variational method is a well-established approach which combines model background information with observations to obtain the “best” initial conditions possible. In the 2-3D-Var version, the fields are adjusted at the analysis time whereas in the 4D-Var flavour, a short-term forecast is run over the selected time window (usually 12 hours) to provide the linearizing trajectory. In 4D-Var the dynamical model is then used as a strong constraint to minimize the difference between the model *forecast* and the observations. This approach is widely used in many NWP centres. The fundamental idea of the variational methods is based on minimization of a cost function which measures the distance between observations and their model equivalent, subject to a background constraint usually provided by the model itself. Optimization of this cost function is performed with respect to selected control variables (e.g., the initial conditions). Adjustments to these control variables allow for the updated model trajectory to match the observations more closely. Assuming the update to the initial condition is small, an incremental formulation can be adopted to ensure a good compromise between operational feasibility and physical consistency in the analysis (Courtier et al., 1994). This so-called “incremental” approach is that followed at ECMWF. Another key aspect of the variational methods is the use of the *adjoint* model to calculate the gradient of the cost function needed in the minimization.

4.2.2 Ensemble methods (MRI/JMA, NRL)

In the MRI/JMA aerosol assimilation system, a four-dimensional expansion of Ensemble Kalman Filter (4D-EnKF) is adopted to assimilate asynchronous observations at the appropriate times. This time-axis expansion (Hunt et al., 2004) allows EnKF to assimilate past and future observations in the same manner as Kalman Smoother (KS) or 4D-Var. Using the 4D-EnKF aerosol assimilation system, the surface emission intensity distribution of dust aerosol is estimated. The vector augmentation mentioned above enables EnKF to estimate the parameters through the background error covariance between dust emissions and observations. Consequently, EnKF simultaneously estimated the aerosol concentrations (as model variables) together with the dust aerosol emission intensity (as model parameters). The MRI/JMA aerosol assimilation system employs the local ensemble transform Kalman filter (LETKF), which is one of the EnKF implementation schemes (Hunt et al. 2007). The LETKF uses the ensemble transform approach (Bishop et al. 2001) to obtain the analysis ensemble as a linear combination of the background ensemble forecasts. The LETKF handles observations locally in space, where all the observations are assimilated simultaneously.

It is important to notice that in the limit of long-window weak-constraint, 4D-Var and ensemble Kalman filter actually converge, as they are both based on the Bayes theorem

which postulates that the probability distribution of the analysis errors is a linear combination of the probability distribution of the observations and background errors (Fisher et al. 2005).

4.3 Observations used for the dust analyses

The MODIS AOD product is the most used aerosol products for analysis, due to its reliability and availability in NRT. The retrievals of aerosol optical depth from MODIS are described by Kaufman et al. (1997) and Remer et al. (2005). Two separate retrievals with different accuracies are applied over land and ocean. The retrievals over land suffer from higher uncertainties due to the impact of the surface reflectance. Several other factors affect the accuracy of the retrievals both over land and ocean: cloud contamination, assumptions about the aerosol types and size distribution, near-surface wind speed, radiative transfer biases, and instrumental uncertainties. These factors are reviewed in detail by Zhang and Reid (2006). It is worth remembering that the MODIS product provides the total aerosol optical depth. The repartition into dust aerosol is completely driven by the type of analysis system and the underlying model.

At the Met Office, the AOD products at 550nm from SEVIRI from Brindley and Ignatov (2006), and Brindley and Russell (2009) are assimilated along with the standard MODIS and Deep Blue (Hsu et al., 2004, 2006; Ginoux et al., 2010) products. However only a subset of observations can be used as the forecast model contains only dust rather than a full suite of aerosols. This is achieved, as far as possible, by geographic filtering of the SEVIRI AOD and by using the MODIS standard product aerosol type flags over land, and for the MODIS deep blue product over bright desert surfaces.

At MRI/JMA the CALIPSO Level 1B data were successfully assimilated to the JMA dust forecast model. CALIPSO (e.g., Winker et al., 2007) is the first satellite mission to have made aerosol lidar observations routinely available. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) carried by CALIPSO provides continuous global measurements using a two-wavelength and polarization-sensitive backscattering lidar, with a very high vertical and horizontal resolution. CALIPSO is in a 705-km sun-synchronous polar orbit between 82°N and 82°S with a 16-day repeat cycle, which is an approximately 1000-km longitudinal interval per day at mid-latitudes. The CALIPSO Level 1B data contains the total attenuated backscattering coefficients at 532 and 1064 nm and the volume depolarization ratio at 532 nm; these values are not contaminated by retrieval errors because they were directly measured and have not been processed by retrieval algorithms.

4.3.1 Data quality aspects and bias correction

Perhaps the most pressing issue for satellite data assimilation is the development of appropriate satellite products, in particular in regard to their error models. Indeed, a key assumption in data assimilation is that the observation errors are uncorrelated spatially. For satellite aerosol products, and dust products in particular, there is considerable spatially correlated bias. Such bias is formed from a number of factors, including biases in the algorithm's lower boundary condition/surface reflectance, microphysical bias in the assumed optical model of the aerosol particles, and cloud mask. These biases can lead to unphysical innovations, which in turn can lead to positive or negative perturbation "plumes" in forecast fields. Currently, prognostic error models are not generated by satellite data providers, and it has fallen on the data assimilation community to modify the products for their own purposes. Debiasing data products and developing reliable point by point uncertainties is time

consuming. Further, aerosol product algorithms update frequently, leaving previous error analyses obsolete

Each centre development team has approached satellite data quality and bias correction differently. Development for FNMOC systems at NRL and the University of North Dakota has favoured extensive error analysis at expense of sophistication of data assimilation technology. MODIS over ocean, land and deep blue products have had extensive debiasing and error modelling applied (Zhang and Reid, 2006; Shi et al, (2011b), Hyer et al., 2011; Shi et al., 2013). In addition, the spatial covariance of the MODIS and MISR products has also been undertaken (Shi et al., 2011a). Internal studies at NRL showed that overall, the assimilation of raw satellite aerosol products reduces model verification scores. After a set of quality assurance steps were taken with the satellite products, NAAPS RMSE error improved by more than 40%.

At ECMWF a variational bias correction is implemented based on the operational set-up for assimilated radiances following the developments by Dee and Uppala (2008). The bias model for the MODIS data consists in a global constant which is adjusted variationally in the minimization based on the first-guess departures. Although simple, this bias correction worked well in the sense that the MACC analysis is not biased with respect to the MODIS observations. Moreover this approach has the advantage to be tied to the optimization of the cost function, and as such it is estimated online, not requiring previous pre-processing of the observations. The bias error model allows more complex treatment with the addition of other bias predictors which are relevant for AOD, for example instrument geometry, viewing angle, cloud cover, wind speed etc. Improvements to the bias model are being currently undertaken.

4.4 Definitions of background and observational errors

Since the relative weight between the background and the observations is decided by the error statistics prescribed for both, in areas that are data-limited such as the deserts, the aerosol analysis is severely under-constrained relative to the observations and relies almost entirely on the background. Also the background matrix is responsible for the redistribution of the aerosol information from the observations to the model fields. This is again especially true for dust due to the already-mentioned paucity of observations over bright surfaces.

4.4.1 Background error covariance matrices

The aerosol background error covariance matrix used for aerosol analyses at ECMWF was derived using the Parrish and Derber method (also known as NMC method, Parrish and Derber, 1992) as detailed by Benedetti and Fisher (2007). This method was long used for the definition of the background error statistics for the meteorological variables and it's based on the assumption that the forecast differences between the 48-h and the 24-h forecasts are a good statistical proxy to estimate the model background errors. The advantage in using the model to define the errors is the grid-point availability of the statistics over a long period. This leads to a satisfactory background error covariance matrix without the need to prescribe the vertical and horizontal correlation length as also shown in Kahnert (2008). However, a shortcoming of this method consists in the static definition of the background error covariance matrix which can lead to sub-optimal analysis in the case of unusual situations such as dust fronts or intense storms. This is addressed by the ensemble methods with the definition of a flow-dependent matrix.

For the FNMOC/NRL NAAPS global model, background error covariance were estimated in a number of methods, all converging to the same number-for global modelling the error covariance length is set to 250 km-the same as is commonly assumed for water vapour. This length was determined from experiments from the MODIS data set. As a check, error covariances were estimated from a three month simulation from the 20 member NAAPS ensemble driven purely from the NOGAPS meteorological ensemble.

4.4.2 Flow-dependent background error covariance matrix

“Errors-of-the-day” can be estimated in the context of the ensemble methods, where at each analysis time a series of forecasts is run starting from perturbed conditions, and these forecasts provide an estimate of the model errors. However, the EnKF tends to be easily influenced by sampling errors at long distances because the available ensemble size is relatively too small to estimate the background error covariance of the atmospheric system. Therefore, the covariance localization must be applied for all the EnKF implementation schemes to reduce the spurious impact of distant observations. The LETKF permits a flexible choice of observations to be assimilated at each grid point. For example, the MRI/JMA system employs the covariance localization with a Gaussian weighting function that depends on the physical distance between the grid location and the observation. The limited ensemble size causes both sampling errors at long distances and filter divergence. To compensate for the error underestimation and avoid the filter divergence, it is necessary to increase the ensemble spread every data assimilation cycle. This technique is called covariance inflation. The MRI/JMA system utilizes a multiplicative inflation method, in which the ensemble spread is uniformly multiplied by a constant value larger than one; it is common to tune this inflation factor empirically. Furthermore, adding random perturbation to the initial state of each ensemble member is sometimes necessary to maintain the diversity of the ensemble members and not to lose the error covariance among the model variables. In the MRI/JMA system, random perturbations are added to dust emission intensity. This type of flow-dependent background error definition is very promising, and it has been progressively adopted for standard meteorological applications also in variational systems through the so-called hybrid approach (Buehner et al, 2010a; Buehner et al 2010b, Clayton et al, 2012), in which the assimilation framework is variational but the background errors of the day are defined through ensemble methods. This approach should work well for dust initialization where the errors on the dust prediction are both associated to emission uncertainties and transport.

4.4.3 Observation errors

The problem of defining appropriate errors for the observations when those are *retrieval products* is very complex. Observation errors for these products are compounded from measurements errors, which depend on the instrument calibration and characteristics; and *a priori* and representativeness errors which depend on the retrieval assumptions regarding the parameters that are not directly observed but that affect the retrieval output and on the overall quality of the forward model used in the retrieval. Most satellite data providers do not provide errors at the pixel levels but provide regression parameters derived from comparison of the satellite products with ground-based equivalent products which are deemed to have high accuracy. This type of regression-based error estimates are very difficult to use in assimilation as they do not faithfully represent the accuracy of the retrieved product at the level of individual pixels, which is what is needed in the assimilation framework. Very often,

the developers end up assigning their own errors to the observations to be able to fit the needs of their system.

For example, at ECMWF the observation error covariance matrix is constructed as being diagonal, to simplify the problem. The errors are also chosen *ad hoc* and prescribed as fixed values over land and ocean for the assimilated observations (MODIS AOD at 550 nm). This was decided after investigation that revealed that biases were introduced in the analysis due to the observation error assumptions when those were specified as *relative* rather than absolute errors. While this might be a specific characteristic of the ECMWF system, the problem of a correct specification of the pixel-level errors on aerosol retrieved products is a topic of much on-going research (Kolmonen et al 2012).

5. Evaluation of atmospheric dust prediction models

5.1 General concepts

An important step in forecasting is the evaluation process of the results that have been generated. This process consists in the comparison of the model results to multiple kinds of observations on different temporal and spatial scales. It facilitates the understanding of the model capabilities, limitations, and appropriateness for the purpose for which it was designed. In this framework, there are three primary objectives in forecast evaluation:

1. Assessing the value of the forecasted variables. The main goal of the evaluation exercise is to evaluate quantitatively and qualitatively whether the modelling system is successfully predicting the temporal and spatial evolution of a particular process.
2. Determining the suitability of a specific application and configuration. Explore the adequacy and correctness of the science represented in the model for the purposes, for which the model is applied. Comparison with other models in addition to the observations can be helpful in identifying the strength and weakness of the system.
3. Guiding improvement. Evaluation results should lead to new directions in model development and improvement

A forecast system is judged solely by its ability to simulate the temporal evolution of chosen forecast variables.

The first evaluation is done right after the forecast period and depends on observations that are made available shortly after they were taken. This type of evaluation, sometimes referred to as verification, is generally part of the operational forecasting process and is therefore done on a regular basis in near-real time (NRT). The end result is the quantification of confidence and predictive accuracy of the model products. An additional and different type of 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 forecast period and observations that were not available for the NRT evaluation can be included. The purpose is to identify potential source to improve the model. In both cases, the evaluation process will depend on the intended use of the forecast product.

5.2 Observational data for evaluation

The first problem that arises when trying to identify appropriate routine measurements for evaluation of dust models is the scarcity of observations intended for the monitoring of dust

events. The location of the main dust sources in unpopulated areas complicates the establishment of observing networks.

Thus, the first option to address the evaluation of dust models has been the use of satellite products. They have the advantage of a large spatial coverage (regional up to global), are made regularly and their observations are made available to weather centres and other institutions shortly after they are taken. The downside is that satellite measurements are highly integrated, not only over the atmospheric column but also over all aerosol components. Therefore, applications involving a particular aerosol type (like mineral dust) must limit to seasons and regions, when or where that type dominates the aerosol composition (Basart et al, 2012). The other limitation also involves the limited aerosol detectability over bright surfaces, which affects instruments operating in the visible part of the spectrum. The new generation of high resolution infrared spectrometers and interferometers on board of polar orbiting satellite (AIRS, IASI) has been shown to have the potential to provide good quality all-weather dust information (Hilton et al, 2012). Algorithms are currently being developed and validated (Peyridieu, et al 2010, Klüser et al, 2011) and it is likely that these products will become prominent both for evaluation and assimilation.

The regions with air quality monitoring networks are the main surface data source for point evaluation of dust concentrations predicted by dust models. This variable reports the conditions of the air we breathe and is therefore one of the most important products supplied by those models. As with the satellites, these measurements integrate the contribution of the different types of atmospheric aerosol. Furthermore, observational values are usually limited to the concentration of particulate matter with an aerodynamic diameter less than 10 micrometres (PM10), which is not always the case of the dust particles suspended in the atmosphere. Finally, it is important to care about the selection of stations, since many of them are located in the cities, industrial parks or roads where human activity is the main source of particles.

Since the data set of weather records provides an excellent spatial and temporal coverage, visibility data included in meteorological observations have sometimes been used as an alternative way to evaluate dust surface concentration forecast by models for regions lacking of an appropriate air quality monitoring network (Shao et al., 2003). Visibility is mainly affected by the presence of aerosol and water in the atmosphere. Therefore, the use of visibility data must be complemented with information on present weather to discard those cases where visibility is reduced by the presence of hydrometeors (fog, rain, etc.). Several empirical relationships between visibility and dust surface concentration can be found in the literature (d'Almeida, 1986; Ben Mohamed et al., 1992; Shao et al., 2003) in order to establish air quality levels in areas with a clear lack of surface concentration observations. However, the validity of these relationships is very limited, because the visibility reduction not only depends on the dust mass concentration, but also on the size spectrum of particles, as well as their density, chemical and mineralogical composition and atmospheric humidity.

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 model evaluation. In particular, the Aerosol Robotic Network (AERONET) is a comprehensive set of continental and coastal sites complemented with several sparsely-distributed oceanic stations that provides large and refined datasets in NRT (Holben et al., 1998; Dubovik and King, 2000). Properties such as aerosol optical depth (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 under cloudy skies and during nighttime. However, these measurements are by far the most commonly used in dust model evaluation.

Finally, lidar and the 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. However, continuous measurements in ground-based stations are only performed in a few stations that are, in general, far from the main dust sources. On the other hand, lidars on board satellites provide global coverage however there temporal coverage is limited.

5.3 Metrics

The evaluation starts with analysis of the plots of the forecasted values against observations for a particular location. This method, typically implemented for NRT monitoring, is very valuable to detect outliers and to identify jumps in performance. Then, the core of the evaluation process 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. The most common metrics used to quantify the departure between modelled and observed quantities are described in Table 3.

Table 3. Definitions of the statistics used in the study, o_i and m_i are respectively observed and modelled values at time and location i , n is the number of data pairs and ($\bar{}$) denotes the mean value.

Validation metrics	Formula	Range	Ideal Score
Mean Bias Error (BE)	$M = \frac{1}{n} \sum_{i=1}^n (m_i - o_i)$	$-\infty$ to $+\infty$	0
Root Mean Square Error (RMSE)	$R = \sqrt{\frac{1}{n} \sum_{i=1}^n (m_i - o_i)^2}$	0 to $+\infty$	0
Correlation coefficient (r)	$r = \frac{\sum_{i=1}^n (m_i - \bar{m})(o_i - \bar{o})}{\sqrt{\sum_{i=1}^n (m_i - \bar{m})^2} \cdot \sqrt{\sum_{i=1}^n (o_i - \bar{o})^2}}$	-1 to 1	1
Gross Fractional Error (FGE)	$F = \frac{2}{n} \sum_{i=1}^n \left \frac{m_i - o_i}{m_i + o_i} \right $	0 to 2	0

Normalized Mean Bias Error (NBE)	$N \quad M = \frac{1}{n} \sum_{i=1}^n \left(\frac{m_i - o_i}{o_i} \right)$	-1 to $+\infty$ for non-negative variables	0
Normalized Root Mean Square Error (NRMSE)	$N \quad R = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{m_i - o_i}{o_i} \right)^2}$	0 to $+\infty$	0

- The mean bias error (BE) captures the average deviations between two datasets. It has the same units as the variable. Values close to 0 are optimal, negative values indicate underestimation and positive values indicate overestimation of the model.
- The root mean square error (RMSE) combines both the bias and the standard deviation. It also has the same units as the variable. 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 the interpretation becomes difficult. The correlation coefficient (r) indicates the extent to which patterns in the model match those in the observations. It is dimensionless.
- The fractional gross error (FGE) is a measure of the overall model error. It ranges between 0 and 2 and behaves symmetrically with respect to under- and overestimation, without over emphasizing outliers.
- The normalized mean bias error (NMBE) and the normalized root mean square error (NRMSE) are dimensionless versions of their counterparts (MBE and RMSE), built to facilitate comparison between the behaviour of different variables.

5.4 Examples of NRT evaluation

The model evaluations for dust forecast are mainly conducted by weather centres generating the forecast or institutions working in collaborations with them. Evaluating the model forecasts against satellite and ground-based observations are used to detect problems early on and also to provide a first indication of the accuracy of the products to the users. In what follows the evaluation systems developed in the framework of the WMO SDS-WAS NAMEE Regional Center and MACCII project are presented here.

5.4.1 The WMO SDS-WAS dust model evaluation initiative

The Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) is a program of the World Meteorological Organization (WMO) with the mission to enhance the ability of countries to produce and deliver to end users timely and precise sand and dust storm forecasts (Terradellas et al., 2011).

As introduced in section 3, the WMO SDS-WAS Regional Centre for Northern Africa, Middle East and Europe coordinates the exchange of forecast products generated by different dust models (BSC-DREAM8b v2, MACC, DREAM8-NMME-MACC, CHIMERE, NMMB/BSC-Dust, MetUM, GEOS-5 and NGAC) and conducts a model inter-comparison and evaluation within its geographical scope (Terradellas et al., 2012).

An exhaustive comparison of different models with each other and against multi-model products as well as observations can reveal weaknesses of individual models and provide an assessment of uncertainties in simulating the dust cycle by the models. Different multi-model products describing centrality (median, mean) and spread (standard deviation, range of variation) are computed to check the possibility of obtaining a more accurate prognosis and to assess the uncertainty of individual models. In particular, the median multi-model is incorporated to the evaluation process. The dust optical depth (DOD) forecast by the models is first drawn together with the AOD AERONET observations in monthly charts for selected dust-prone stations. Then, different evaluation metrics (see Table 2) are computed in order to quantify the agreement between predictions and observations for individual stations and different regions (Sahara-Sahel, Middle East and Mediterranean) as well as different temporal scales (monthly, seasonal and annual basis).. Calculations are restricted to observations with low Ångström exponent (AE) values (< 0.6) to ensure that forecast and observations are only compared during episodes where dust is the largest contributor. However, there will always be a small portion of particles from other sources, so a small negative bias can be expected.

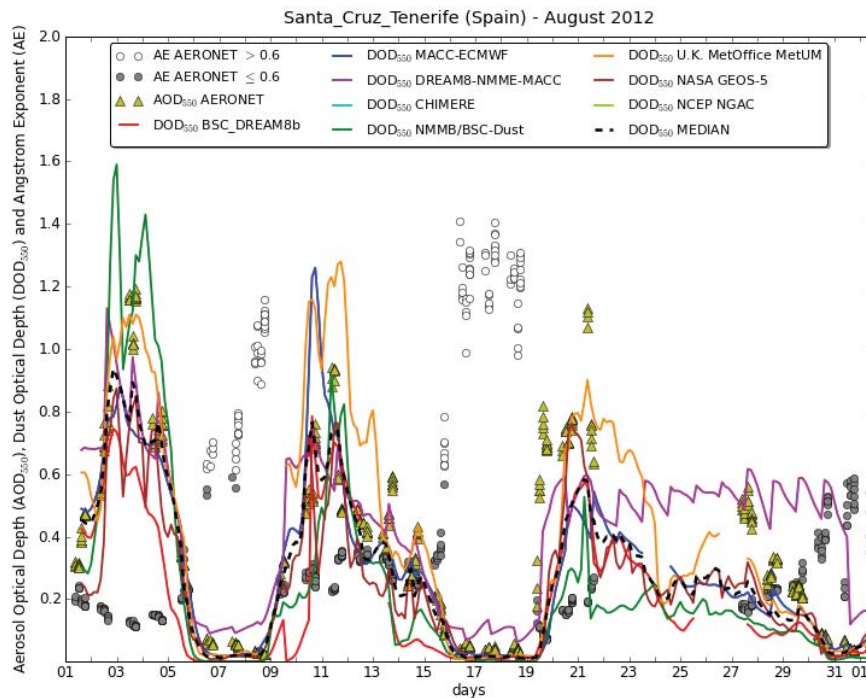


Figure XX.6. Time series of aerosol optical depth at Santa Cruz de Tenerife (Canary Islands, Spain) for August 2012. The plot shows the dust optical depth forecast by the different models (solid lines), the median value (dashed black line) and direct-sun AERONET observations (yellow triangles). An Ångström exponent (AE) lower than < 0.6 (dark grey dots) indicates that the observed AOD (yellow triangles) is associated to the presence of desert dust.

5.4.2 The MACC-II evaluation

Monitoring Atmospheric Composition and Climate (MACC II) is the current pre-operational atmospheric service of the European Global Monitoring for Environment and Security (GMES) program. MACC-II uses a comprehensive global monitoring and forecasting system that estimates the state of the atmosphere on a daily basis, combining information from models and observations, and it provides a daily 5-day forecast. The global modelling system is also used to provide the boundary conditions for an ensemble of more detailed regional air quality models that are used to zoom in on the European domain and produce 4-day forecasts of air quality.

The dust optical depth (DOD) at 550 nm forecast by the MACC model, as well as the contributions of other aerosol types, are drawn together with the AERONET and MODIS retrievals of AOD in monthly charts for selected stations. However, the scoring metrics that are calculated on a monthly-averaged time frame for different regions or stations are always calculated for the total atmospheric aerosol, without any distinction of the species. This evaluation is complemented with regular reports describing the model performance to forecast major and recent events (available online at www.gmes-atmosphere.eu).

As part of the evaluation, a large effort has been devoted to the investigation of how to best use ground-based measurements, such as AERONET, to assess the models in data-scarce regions. Calculating scores is made complicated by the geographical inhomogeneity of the observation sites. AERONET sites are not spread evenly over the globe, but are far more concentrated in developed and densely populated parts of the world such as Europe and the USA. Taking simple means over the sites therefore leads to scores which are biased towards given regions, which is not a desirable feature. In addition, any systematic changes in the geographical spread of the sites over time may lead to corresponding systematic changes in the scores. Long-term time-series of the scores could then reflect changes in the observing system more than changes in forecast quality, which is not the objective.

In order to reduce geographical bias and increase long-term stability model-versus-AERONET scores are computed using weights for each observation that reflect the local observation density at each observation time. Remote observations with no close neighbours receive a maximum weight, whereas observations closely surrounded by others receive a reduced weight. The precise procedure utilises "Voronoi polygons" principles.

For a given set of points in space, the Voronoi polygon around a given point is the region closer to that point than any other. At each observation time the Voronoi polygons are calculated on the sphere for all available observations. The areas of the polygons are then computed and these become the observation weights. Thus observations in data-dense areas naturally receive lower weights than those in data-sparse areas. To prevent observations in very data-sparse areas receiving unnaturally high weights the polygon edges are limited to a maximum radius. Given that the choice of this radius is subjective, a good value was found to be that which results in a maximum polygon area of 1% of the total area being scored.

5.4.3 Case study evaluation

An exhaustive comparison of model outputs against other models and observations can reveal weaknesses of individual models and provide an assessment of uncertainties in simulating the dust cycle. Model inter-comparisons are especially useful for evaluating different components of the models involved since different approaches to simulate the same event are contrasted. This approach can give additional information on sources for potential model improvement.

The choice of the dust event to be studied is the first step in this kind of evaluation. The selection of the event will depend on the aspects of the dust cycle that one wants to examine, but, in general, events that stand out because of their intensity and/or their far outreach are chosen. For this kind of study, one can use the observations available at the NRT evaluation, but also measurements made available since the occurrence of the event. In addition, not only observations directly linked to the forecasted variable (e.g. surface concentration) are used, but multiple and different observations are combined to deliver a detailed idea of the structure and evolution of the dust cloud and the state of the atmosphere at the different stages of the event. Observations detailed in section 5.2 are usually complemented with strictly meteorological observations such as wind speed and direction at the surface and wind profile within the atmospheric boundary layer. The wind speed allows exploring the model's performance to simulate the dust release while the vertical profile gives insight on the model's capacity to reproduce the conditions determining the dust transport.

Multiple case studies concerning a single model can be found in the literature (e.g. Perez et al., 2006b; Heinold et al., 2007; Cavazos et al., 2009). On the other hand, inter-comparisons of multiple models simulating the same event are described by Uno et al. (2006) and Todd et al. (2008). The former compared multiple regional dust models over Asia, while the latter compared five regional models for a 3-day dust event over the Bodélé depression. Both studies reveal the ability of models to reproduce the onset and duration, but not the magnitude of a given dust event. Furthermore, even though the models were able to reproduce surface measurements, large differences existed among them in processes such as emission, transport and deposition. Shao et al. (2003) not only evaluated the model performance to simulate a specific dust event, but also the model capacity to predict the event for different lead times. The authors found that the predicted quantities agreed well with the observations.

Inter-comparison studies are not necessarily limited to a single event. They can analyze the models performance to simulate the dust cycle during an extended time period and provide additional and valuable information for model improvement. A broad inter-comparison of 15 global aerosol models was conducted within the framework of the aerosol inter-comparison project (AeroCom; <http://aerocom.met.no/>; Huneus et al., 2011). Each model was compared to observations of total AOD, dust deposition, Ångström exponent (AE, coarse mode fraction AOD and dust surface concentrations. The study revealed a generalized better skill to simulate vertically-integrated variables, such as AOD, than dust concentration at the surface.

6. Future outlook

Dust numerical prediction is a growing area of research with many operational applications. In the last few years, many centres have started activities to provide dust forecasts to interested stakeholders, who range from solar energy plant managers to health and aviation authorities, from policy makers to climate scientists. There is also a growing interest in understanding how dust impacts the general circulation of the atmosphere through its radiative effects which could help in improving numerical weather prediction and projections of climate change. Dust forecast models have reached a high degree of complexity and can provide useful information to forecasters. Some factors limiting the accuracy of the models are related to the complex emission sources and the characteristics of the emitting surfaces, including texture, composition, vegetation type and topography. Dust prediction is also limited by the paucity of observations available for data assimilation, model initialization and verification. As more products from satellite and ground-based stations become available it is foreseeable that dust prediction will improve. In order to provide the best dust forecasts possible, along with improving the dust models, there are currently international efforts to

bring together several operational and quasi-operational models to form multi-model ensembles. The merit of these ensembles is to bring together the strengths of the various state-of-the-art models while offering the possibility to approach the dust prediction from a probabilistic perspective, thus enhancing the range of applications. The development of these multi-model ensembles is still at an early stage, and exploitation of their potential is still limited, also because of the relatively small number of participating models. However, it is anticipated that the probabilistic approach to dust prediction both at level of the individual centres and within the context of the multi-model ensembles will become more important in the future.

7. References

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Table 1. Global model synopsis

<i>Model</i>	GEOS-5	MACC	MASINGAR	MetUM	NAAPS	NGAC	NMMB/BSC-Dust
<i>Institution</i>	NASA	ECMWF	JMA/MRI	U. K. Met office	FNMOC/NRL	NCEP	BSC-CNS
<i>Meteorological driver</i>	GEOS-5	ECMWF	MRI/JMA98 AGCM	MetUM	NOGAPS	NEMS GFS	NMMB/NCEP
<i>Source mask</i>				HWSD, FAO (2009)		Ginoux et al., (2001)	USGS-FAO with Ginoux et al. (2001) and NESDIS
<i>Emission scheme</i>	Based on Ginoux (2001)	Uplifting (Ginoux et al., 2001; Morcrette et al., 2008, 2009)	Uplifting (Gillette, 1978; Tegen and Fung, 1994)	Woodward (2001, 2011)	Walker et al. 2009	Dust uplifting following Ginoux (2001)	Saltation and sandblasting (White, 1979; Marticorena and Bergametti, 1995)
<i>Deposition schemes</i>	Colarco et al (2010)	Wet/dry deposition, in-cloud and below cloud scavenging Morcrette et al. (2009)		Wet/Dry deposition (Woodward, 2001)		Colarco et al. (2010)	Dry deposition (Zhang et al., 2001) and wet deposition (Ferrier et al., 2002; Betts, 1986; Janjic, 1994)
<i>Sedimentation scheme</i>	Colarco et al (2010)	Tompkins (2005)		Woodward, 2001			Zhang et al. (2001)
<i>Horizontal resolution</i>	0.25° x 0.3125°	1° x 1°	1.125° x 1.125°	0.3516° x 0.2344°	1 degree	T126 (~ 1 deg)	140625.° x 1°)
<i>Vertical resolution</i>	72 layers. Top: 0.01 hPa	60 σ -layers	20 σ -p hybrid layers	70 levels. Charney-Phillips grid	25 layers	64 sigma-pressure hybrid layers, Top at 0.2 hPa	40 σ -hybrid-layers
<i>Height first layer</i>		10 m (above the surface)	40m	20 m		20 m	
<i>Radiation interactions</i>	Direct effects fully included	Yes (not activated)	No	Yes (not activated)	No	Yes (not activated)	Yes (not activated)
<i>Transport size bins</i>	5 bins centered at (0.73 μ m, 1.4 μ m, 2.4 μ m, 4.5 μ m, 8.0 μ m)	3 bins (0.03-20 μ m)	10 bins (0.1-10 μ m)	2 (0.1-10 μ m)	1	5 bins centered at (0.73 μ m, 1.4 μ m, 2.4 μ m, 4.5 μ m, 8.0 μ m)	8 bins (0.1-10 μ m)

<i>Data assimilation</i>	Yes	Yes AOD550/MODIS	No	Yes AOD550/MODIS	Yes	No	No
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<i>Model</i>	BSC-DREAM8b	CHIMERE	CMAQ-KOSA	COAMPS	CUACE/Dust	DREAM8-NMME-MACC	NMMB/BSC-Dust	TAQM-KOSA
<i>Institution</i>	BSC-CNS	LMD	NTU/TEPA	FNMOCC/NRL	CMA/CAMS	SEEVCCC	BSC-CNS	NTU/TEPA
<i>Meteorological driver</i>	Eta/NCEP	MM5	MM5/WRF	COAMPS		NMME/NCEP	NMMB/NCEP	MM5/WRF
<i>Meteorological initial fields</i>	Regional	NCEP/GFS	NCEP/GFS	COAMPS		Regional	Regional	NCEP/GFS
<i>Source mask</i>	NCEP/GFS		Wang et al. (2000) + MODIS land type		Gong et al., 2003b; Zhang et al., 2003	ECMWF	NCEP/GFS	Wang et al. (2000)
<i>Emission scheme</i>	USGS-FAO with Ginoux et al. (2001)	Saltation and sandblasting (Marticorena and Bergametti, 1995; Alfaro and Gomes, 2001; Menut et al., 2005)	Uplifting (Wang et al. 2000)	Walker et al. 2009	Marticorena and Bergametti (1995), Alfaro et al. (1997), Alfaro and Gomes (2001)	USGS-FAO with Ginoux et al. (2001)	USGS-FAO with Ginoux et al. (2001) and NESDIS	Uplifting (Wang et al. 2000)
<i>Deposition schemes</i>	Uplifting (Shao et al., 1993; Janjic et al., 1994)		dry deposition and below cloud scavenging (CMAQ; Byun and Schere, 2006)			Uplifting (Shao et al., 1993; Janjic et al., 1994)	Saltation and sandblasting (White, 1979; Marticorena and Bergametti, 1995)	dry deposition and below cloud scavenging (RADM2; Stockwell et al., 1990)
<i>Sedimentation scheme</i>	Dry deposition (Zhang et al., 2001) and below cloud scavenging (Nickovic et al., 2001).		Gravitational settling (CMAQ; Byun and Schere, 2006)			Dry deposition (Zhang et al., 2001) and below cloud scavenging (Nickovic et al., 2001).	Dry deposition (Zhang et al., 2001) and wet deposition (Ferrier et al., 2002; Betts, 1986; Janjic, 1994)	Gravitational settling (RADM2; Stockwell et al., 1990)
<i>Horizontal resolution</i>	1/3 ^o x 1/3 ^o	1 ^o x 1 ^o	81 km and 57 km	1-81 km		0.25 ^o x 0.25 ^o	1.3. ^o x 1.3 ^o	81 km and 57 km (3 km for local dust)
<i>Vertical resolution</i>	24 Eta-layers	30 σ -layers	15 σ -layers	48 layers		24 σ -hybrid-layers	24 σ -hybrid-layers	15/19 σ -layers
<i>Height first layer</i>	86 m (above sea level)	40 m (above the surface)	40 m (above the surface)			86 m (above sea level)	100 m (above surface)	40 m (above surface)
<i>Radiation interactions</i>	Yes	No	No	No		No	Yes (not activated)	No
<i>Transport size bins</i>	8 bins (0.1-10 μ m)	9 bins (0.039-20 μ m)	12 bins (0.1-24.6 μ m)	User defined bins 0.1-35 μ m		8 bins (0.1-10 μ m)	8 bins (0.1-10 μ m)	12 bins (0.1-24.6 μ m)
<i>Data assimilation</i>	No	No	No	No	Yes	Yes, MODIS-MACC	No	No

Table 2. Regional models synopsis.**Acronyms**

AD-Net	Asian Dust Network
AERONET	Aerosol Robotic Network
AOD	Aerosol Optical Depth
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CMAQ-KOSA	CMAQ coupled with dust deflation module
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GEMS	Global Earth-system Monitoring using Space and in-situ data
GMAO	Global Modeling and Assimilation Office
ICAP	International Cooperative for Aerosol Prediction
JMA	Japan Meteorological Agency
LMD	Laboratoire de Météorologie Dynamique
LOA	Laboratoire d'Optique Atmosphérique
LSCE	Laboratoire des Sciences du Climat et l'Environnement
MACC	Monitoring Atmospheric Composition and Climate
MISR	Multi-angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NRL	Naval Research Laboratory
NRT	Near Real Time
NTU	National Taiwan University
RMS	Root Mean Square
RMSE	Root Mean Square Error
SEVIRI	Spinning Enhanced Visible and Infrared Imager
TAQM	Taiwan Air Quality Model
TAQM-KOSA	TAQM coupled with dust deflation module

TEPA	Taiwan Environmental Protection Administration
UKMO	United Kingdom Meteorological Office
WMO	World Meteorological Organization
SDS-WAS	Sand and Dust Storm Warning Advisory and Assessment System