The impact of data assimilation on the prediction of Asian desert dust using an operational 4D-Var system

Angela Benedetti[1], Francesca Di Giuseppe[1], Luke Jones[1], Vincent-Henri Peuch[1], Samuel Rémy[2], and Xiaoye Zhang[3,4]

[1]European Centre for Medium Range Weather Forecast (ECMWF), Reading, UK
[2]Institut Pierre-Simon Laplace, CNRS / Sorbonne Université, Paris, France
[3]State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, China
[4]Center for Excellence in Regional Atmospheric Environment, INE, CAS

Correspondence to: Angela Benedetti (A.Benedetti@ecmwf.int)

Abstract. Asian Dust is a seasonal meteorological phenomenon which affects East Asia, and has severe consequences on the air quality of China, North and South Korea and Japan. Despite the continental extent, the prediction of severe episodes and the anticipation of their consequences is challenging. Three one-year experiments were run to assess the skill of the model of the European Centre for Medium-Range Weather Forecasts (ECMWF) in monitoring Asian dust and understand its relative

5   contribution to air quality over China. Data used were the MODIS Dark Target and the Deep Blue Aerosol Optical Depth. In particular the experiments aimed at understanding the added value of data assimilation runs over a model run without any aerosol data. The year 2013 was chosen as representative for the availability of independent Aerosol Optical Depth (AOD) data from two established ground-based networks (AERONET and CARSNET), which could be used to evaluate experiments. Particulate Matter (PM) data from the China Environmental Protection Agency (CEPA) were also used in the evaluation. Re-

10   sults show that the assimilation of satellite AOD data is beneficial to predict the extent and magnitude of desert-dust events and to improve the forecast of such events. The availability of observations from the MODIS Deep Blue algorithm over bright surfaces is an asset, allowing for a better localization of the sources and definition of the dust events. In general both experiments constrained by data assimilation perform better that the unconstrained experiment, generally showing smaller mean normalized bias and fractional gross error with respect to the independent verification datasets. The impact of the assimilated

15   satellite observations is larger at analysis time, but lasts well into the forecast. While assimilation is not a substitute for model development and characterization of the emission sources, results indicate that it can play a big role in delivering improved forecasts of Asian Dust.

1 Introduction

Asian Dust (AD) is a seasonal meteorological phenomenon which affects East Asia, particularly during spring. Dust is transported from the deserts of Mongolia, northern China and Kazakhstan and can travel over long distances affecting air quality of China, North and South Korea and Japan. Occasionally, the dust can even be transported over the ocean over thousands of

5   kilometers and reach the coasts of North America. Measurements at Manua Loa, Hawaii show presence of dust of Asian origin (Shaw, 1980; Darzi and Winchester, 1982; Holmes and Zoller, 1996).

Dust is becoming a more serious concern due to the increase of industrial pollutants contained in it, also in connection to intensified desertification in China causing longer and more frequent occurrences, both linked to climate factors and to land use change in West Asia (Zhang et al., 2003; Chuluun and Ojima, 2002). Areas affected by dust experience poor air quality and,

10 as a consequence, dust is known to cause a variety of health problems, including sore throat and asthma in otherwise healthy people. Often, people are advised to avoid or minimize outdoor activities, depending on the severity of the storms. For those already with asthma or respiratory infections, dust-related pollution can be fatal (Lee et al., 2013; Goudie, 2014; Chen et al., 2011). The economic impact of dust storms connected to reduced air visibility, canceled flights, and disrupted ground travel can also be high (Jeong, 2008).

15 Because of its health, social and economical impacts, it is critical to understand the source strength, transport and deposition of dust and to establish Sand and Dust Storms (SDS) forecasting and early warning capabilities. Under the auspices of the World Meteorological Organization (WMO), the need for a global SDS forecasting and early warning system was highlighted since 2005ch is . More than forty member countries expressed interest in participating in activities to improve capacities for more reliable SDS monitoring, forecasting and assessment. The SDS-WAS (Warning and Assessment System) was launched

20 in 2007 with the mission to enhance the ability of countries to deliver timely and quality sand and dust storm forecasts, observations and information to users through an international partnership of research and operational communities. Towards this goal, three regional centers have been created: the North Africa-Middle East-European (NAMEE) node, the Pan-American node and the Asian node. The latter is hosted by the Chinese Meteorological Administration (CMA) and its focus is Asian dust prediction (Zhang and coauthors, 2015). Member countries of the Asian node include Japan, Korea, Mongolia and Kazakhstan.

25 All centres run their forecast models for the specific region (Gong and Zhang, 2008; Park et al., 2010). Some models such as that of the Japan Meteorological Agency run at the global scale (Tanaka and Chiba, 2005). The European Centre for Medium-range Weather Forecast (ECMWF) also contributes its dust forecasts to the Asian node through a partnership between the Copernicus Atmosphere Monitoring Service (CAMS) and CMA[1].

Despite the recognized relevance, Asian dust forecast is still a challenge due to the poor characterization of the sources, which

30 have strong spatial and temporal variability and the paucity of observational data available to characterize both emissions and transport especially in Near-Real-Time (NRT). A study by Uno et al. (2006) compared eight state-of-the-art dust models and showed that emission fluxes from the Taklimakan Desert and Mongolia strongly differ among the models. They suggested that measurements of dust flux and accurate updated land use information are important to improve the models over these regions.

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[1]See http://eng.nmc.cn/sds_was.asian_rc/ for further reference

They also found that modeling of dust transport and removal processes over key regions needs to be improved in order to obtain more skillful dust prediction that could underpin warning systems, improve preparedness and possibly lessen the impacts.

Although modeling problems need to be tackled at the level of the parameterization of the physical, dynamical and radiative processes, data assimilation of dust-related observations such as optical depth and lidar backscatter from satellite sensors can help alleviate problems and improve the forecast of dust events. This has been shown for example in a pioneering work by Sekiyama et al. (2010) where the authors show that assimilation of data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar in an Ensemble Kalman filter framework improves the model simulation of Aeolian dust events. Assimilation efforts to specifically improve dust prediction have been undertaken at the global and regional scale by several institutes both with ensemble methods where also emissions are perturbed (Lin et al., 2008; Rubin et al., 2016; Di Tomaso et al., 2017) and variational methods (Niu et al., 2008; Liu et al., 2011). All studies show the positive impact of satellite and in-situ data assimilation in desert dust-affected regions for high load episodes, with some impact lasting into the forecast range.

Progress has been made in recent years thanks to the deployment of accurate, multi-channel aerosol sensors on satellite platforms and the improvement of ground-based networks which are now offering stable observations of good quality over long period and increasingly in NRT. Given these opportunities in this paper, we will investigate the added benefit of data assimilation for the desert dust prediction using ECMWF's Integrated Forecasting System (IFS) and AOD observations from MODIS which are now also available on bright surfaces (Deep blue collection) in the framework of the 4D-Var assimilation system extended to aerosol species (Courtier et al., 1994; Benedetti et al., 2009). The novelty with respect to previous studies that also employed MODIS observations (i.e. Liu et al. (2011)) rests in the use of a fully *operational* 4D-Var system in which the model dynamics serve as a constraint during the assimilation. For dust storms of synoptic extent, this constraint might imply a longer-lasting impact of the assimilated data into the forecast range. The verification of the analysis and forecast benefits from the availability of data from the Aerosol Robotic Network (AERONET, Holben et al. (1998, 2001)), as well from the China Aerosol Remote Sensing Network (CARSNET, Che et al. (2015)). Additionally, PM data from CEPA are also used to assess the performance of the assimilation.

2   Description of the ECMWF/CAMS system

Desert dust forecasts are provided by the ECMWF/CAMS system which is a comprehensive modeling and assimilation system based on the IFS developed at ECMWF with the extended capabilities of including atmospheric composition tracers in the transport model and in the analysis(Flemming et al., 2015). The system has been developed in the CAMS precursor projects, Global and Regional Earth System Monitoring Using Satellite and In Situ Data (GEMS, Hollingsworth et al. (2008)) and Monitoring Atmospheric Composition and Climate (MACC, Peuch and Engelen (2012)). Aerosols are forecast within the ECMWF/CAMS global system by a forward model (Morcrette et al., 2009), based on earlier work by Reddy et al. (2005) and Boucher et al. (2002) that uses five species: dust, sea salt, black carbon, organic carbon and sulfates.

Dust aerosols specifically are represented by three prognostic variables that correspond to three size bins, with bin limits of 0.03, 0.55, 0.9 and 20 μm radius. Specific dust processes that are parameterized are production of dust through saltation and removal by wet and dry deposition and sedimentation. Various areas are marked as having potential to emit dust based on surface albedo, moisture of the top soil level and bare soil fraction. Dust emissions are parameterized following Ginoux et al.

5   (2001) as a function of the cubic power of 10m wind speed. A correction is also applied to account for gustiness as described in Morcrette et al. (2008). Dry deposition depends on a prescribed deposition velocity and on aerosol concentration in the model level closer to the surface. Sedimentation is applied only to the largest dust bin and depends on a fixed settling velocity and the dust concentration at each model level.

For sea-salt, a bin representation is used and emissions are also parameterized as a function of surface winds. For all other

10   tropospheric aerosols (carbonaceous aerosols and sulfates), a bulk parameterization is used and emission sources are defined according to established inventories (Lamarque et al., 2010). Biomass burning emissions contributing to black carbon and organic matter loads are prescribed from the Global Fire Assimilation System (GFAS,Kaiser et al. (2012)). Removal processes include sedimentation of all particles, wet and dry deposition and in-cloud and below cloud scavenging. A simplified representation of the sulfur cycle is also included with only two variables, sulfur dioxide (SO_2) acting as a precursor for sulphate (SO_4)

15   in particulate form. Overall, a total of 12 additional prognostic variables for the mass mixing ratio of the different components (bins or types) of the various aerosols are used in this configuration. The ECMWF/CAMS system also includes chemically reactive tracers such as ozone, carbon monoxide, NOx, formaldehyde as well as greenhouse gases.

The ECMWF/CAMS system is used operationally to provide global forecasts of aerosols, reactive gases and greenhouse gases as well as boundary conditions for higher resolution regional models proving air quality forecasts over Europe. Data are

20   freely available from the CAMS website.

3   Methodology and experimental set-up

The ECMWF/CAMS system also runs a 4D-Var assimilation of satellite and ground-based data for the meteorological variables as well as the atmospheric composition variables. The aerosol assimilation uses total aerosol mixing ratio as a control variable.Each aerosol species is assumed to contribute to the total aerosol mixing ratio according to a fractional contribution which

25   is assumed constant over the 12-hour assimilation window. At the end of the minimization, the increments in total aerosol mixing ratio are distributed to the individual species according to their fractional contribution to the total mass. A forward model is used to calculate the Aerosol Optical Depth (AOD) from the individual components using a look-up table approach. The aerosol optical properties are prescribed according to Bozzo et al. (2017). During the minimization, the tabulated optical properties of the individual species are retrieved and used in the calculation of the total extinction. The vertical integral of the

30   extinction profile provided the total AOD, which is the observed quantity, at every observation location.

AOD data at 550nm from the Moderate Resolution Imaging Spectro-radiometer (MODIS) sensors on board of the Terra and Aqua satellites have been assimilated in the ECMWF'4D-Var system since 2008 (Benedetti et al., 2009). Initially, only the Dark Target product was used (Levy et al., 2010). Since 2015, both MODIS Dark Target and Deep Blue (Hsu et al., 2013) data

are used. Deep Blue offers the advantage to provide Aerosol Optical Depth(AOD) retrievals over bright surfaces, which is of particular interest for getting insight on dust sources by means of data assimilation. It can be assumed indeed that over deserts the biggest contribution to AOD comes from dust aerosols, even if the analysis uses total AOD and the other aerosol species are also included. Recently, MODIS Collection 6 has become available (Levy et al., 2013; Sayer et al., 2013, 2014) and this is

5   the collection that has been used in this study.

The operational ECMWF/CAMS systems also uses AOD data from the Polar Multi-Sensor Aerosol Optical Properties — Metop (PMAP) product, operationally provided by EUMETSAT, but this product was not used in the experiments outlined in this paper.

To investigate the impact of the assimilation on the dust prediction, three experiments were set-up for the whole of 2013:
10   one experiment with 4D-Var data assimilation of MODIS Col 6 with the exclusion of Deep Blue data (indicated hereafter as DT), one experiment with 4D-Var assimilation of MODIS Col 6 data with the inclusion of Deep Blue data (indicated as DTDB) and one control experiment with free-running aerosols (indicated as CONTROL). In the control experiment there are no aerosol data being assimilated in the analysis. In this paper, we focus on results during March 2013, when several marked events occurred.

15   The horizontal resolution of the operational version run in the context of CAMS is currently 40km with 60 vertical levels and model top at 0.1 hPa. The experiments shown here were run with a previous version of the system with horizontal resolution of 80km and the same number of vertical levels.

4   Outcomes of the investigation

4.1   Comparisons with independent AOD datasets

20   Results from the experiments (DT, DTDB and CONTROL) are presented in what follows. Comparisons were made with independent datasets from AERONET and CARSNET. AERONET are routinely used for the verification of the ECMWF/CAMS forecasts, but this is the first time that the CARSNET dataset has been used in this context. Model data was bilinearly interpolated to the AERONET/CARSNET site locations and then averaged over 24 hour periods (from T+3 to T+24). AERONET data is similarly averaged, with each data value receiving a weight proportional to the time difference between the data values
25   before and after it, up to a maximum of three hours. The CARSNET data used was already in the form of daily averages and no further averaging was done.

While the entire year was considered, we focus in this paper on the spring season when Asian dust is at its peak due to the seasonal increased frequency of cyclonic weather systems with associated high surface wind speeds. At this time of the year the contrast between warm air masses in the south and cold air masses from Siberia and Mongolia is maximum. The high
30   N-S thermal gradient can give rise to situations characterized by a high baroclinic instability, with the development of fast developing and moving lows associated with high winds over the dust emitting regions of the Gobi desert and inner Mongolia.

As an example of the extent of this type of events, 1 shows the March 9th dust storm as simulated by the ECMWF model along with the coverage provided by the MODIS Dark Target and Deep Blue AOD retrievals. Comparing with the satellite

image on the same day (figure 2), courtesy of NASA, the forecast shows a good degree of qualitative agreement with the observations.

This particular dust storm was analyzed in detail by Chauhan et al. (2016). The storm originated at the Mongolian border and dust was first transported to Northeastern China and further transported to the southwest. The air quality in Beijing was

5 severely affected as the sandstorm spread. The dust further propagated to the Korean Peninsula and Japan. The analysis of other similar events during the spring season confirms what is outlined below.
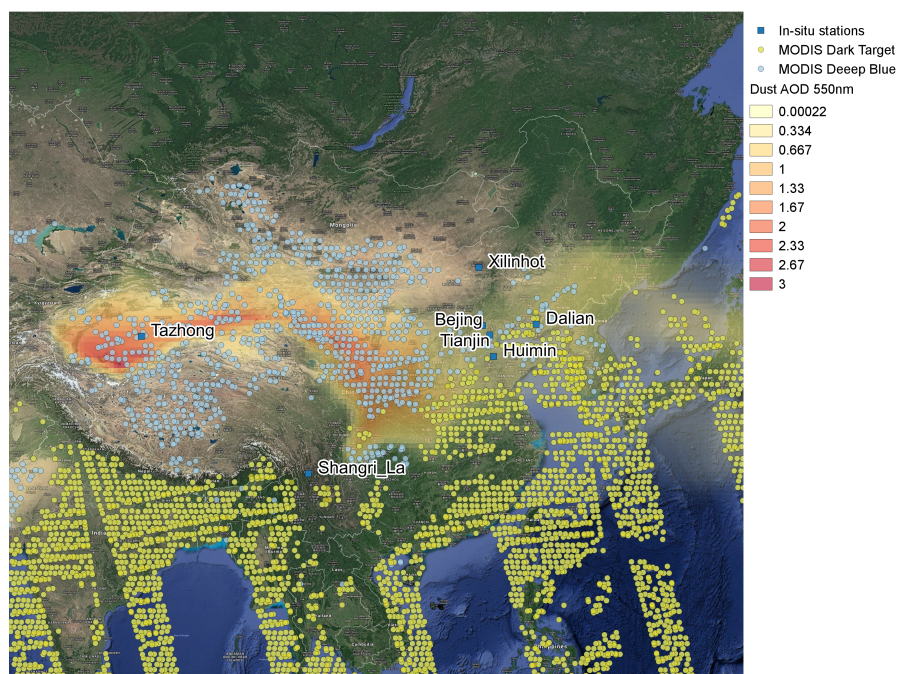
Figure 1. Desert Dust event forecast by the CAMS system for the 9th of March 2013 (shaded) with observation locations from the Dark-Target (yellow dots) and the deep-blue algorithms (blue dots) from MODIS Collection 6 used in the assimilation experiments. A few in situ verification stations are also highlighted. For these stations detailed results are provided.

Figure 3 shows a first look at the model performance via scatterplots of model versus observed values of AOD at 1020 nm for the month of March 2013. All stations are considered together. Data are plotted for the South-East Asia area (23S-50N, 65E-180E). Visual inspection of the plots shows that both assimilation experiments have a more similar distribution than the

10 control experiment with respect to the observations, particularly for large dust events (red colors). The mean of the observations is 0.2533 versus 0.2012 for experiment CONTROL, 0.2503 for experiment DT and 0.2437 for experiment DTDB. Correlation is the highest for experiment DTDB at 0.7618 versus 0.7498 for experiment DT and 0.7399 for experiment CONTROL.

The statistical indicators presented here are Fractional Bias (FB, sometimes also referred to as Modified Mean Normalized Bias) and Fractional Gross Error (FGE), although other indicators have been analyzed and have been found to lead to similar
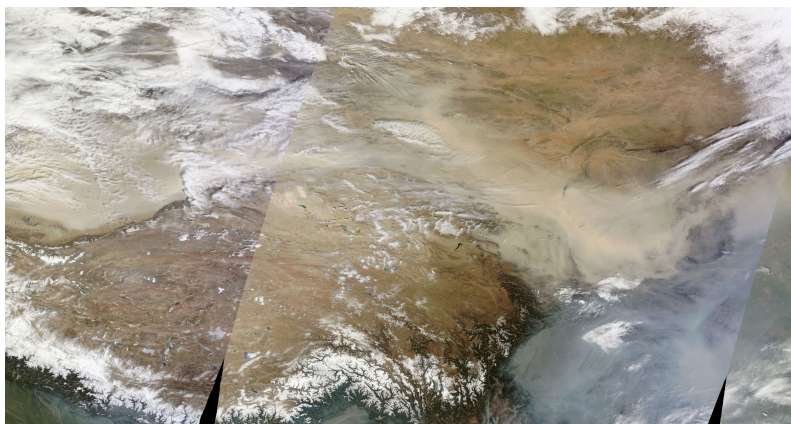
Figure 2. NASA Worldview image for March 9, 2013. Available at https://go.nasa.gov/2FI0vbI.
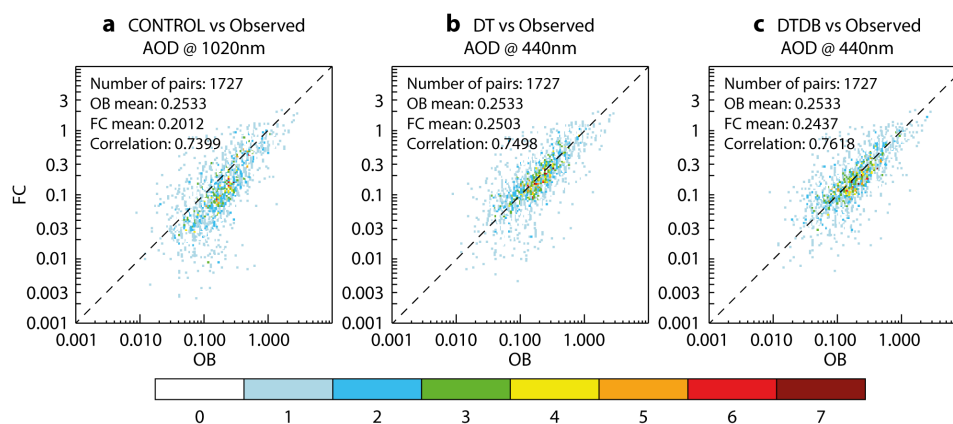
Figure 3. Scatterplot of modeled versus observed AOD at 1020 nm for all stations (83 in total) in the South-East Asia area (23S-50N, 65E-180E). Left panel shows experiment CONTROL, middle panel shows experiment DT and right panel shows experiment DTDB.

conclusions. The mathematical definitions for these parameters are the following:

$$FB = \frac{2}{n} \sum_{i=1}^{n} \frac{f_i - o_i}{f_i + o_i} \tag{1}$$

$$FGE = \frac{2}{n} \sum_{i=1}^{n} \frac{\mid f_i - o_i \mid}{\mid f_i + o_i \mid} \tag{2}$$

where f_i is the model output and o_i are the observations. n represents the total number of observations. The FB is normalized
5   to make it non-dimensionless. It varies between $+2$ and -2 and has an ideal value of zero for perfect model (and perfect observations). The FGE ranges between 0 and 2 and behaves symmetrically with respect to under- and overestimation, without over-emphasizing outliers (as instead the root mean square error does).

Figure 4, shows maps of FB for Aerosol Optical Depth (AOD) at 440 nm with respect to all AERONET and CARSNET sites for March 2013 over the South-East Asian region at the analysis time. Within a certain margin of noise, it is possible to see that the performance of both experiments including assimilated MODIS data is more skillful than that of the control experiment. The figure also shows that including the Deep Blue data, which provide Aerosol Optical Depth information over
5   bright surfaces, helps to further reduce the bias with respect to the ground-based observations. Figure 5 shows maps of FGE and confirms that the error with respect to the independent observations is reduced in the runs with assimilated satellite data.

Time-series of FB and FGE average over South-East Asia are shown in figure 6. Again, the improvement in bias and error in the assimilation experiments is visible, particularly for the AERONET stations. The model has generally a larger bias when compared to the CARSNET observations, particularly for the CONTROL experiment. Yet again the experiments with
10   assimilated satellite data perform visibly better than the CONTROL. If we focus on the FGE, its average value on March 9 is particularly large for the CARSNET stations reaching values of 1. However, the reduction in error due to the MODIS Deep Blue (experiment DTDB, gray line) data is of the order of 20%. However, on other dates such as March 1, the improvement is more marked and the FGE is reduced by more than 60% from values above 1 in the CONTROL experiment to values of 0.5 in the DTDB experiment. This indicates again the additional benefits of including observational satellite information over source
15   areas.
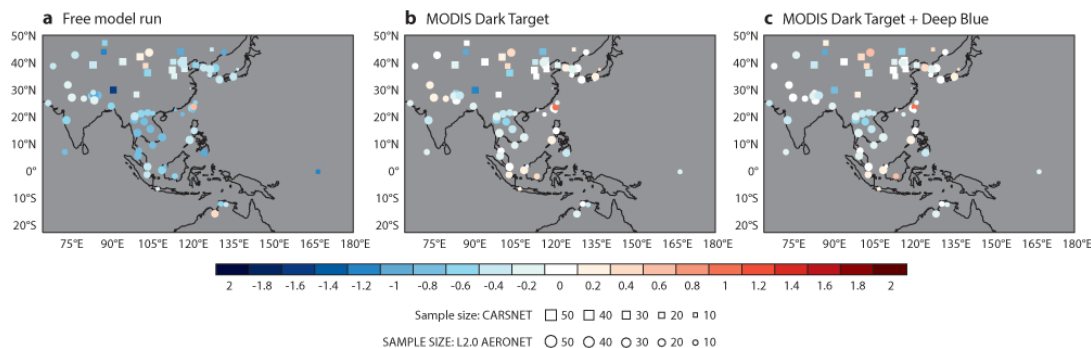
Figure 4. Fractional Bias for Aerosol Optical Depth at 440nm with respect to AERONET (circles) and CARSNET (squares) data: panel (a) shows the experiment CONTROL, panel (b) shows experiment DT (with only Dark Target MODIS retrievals in the assimilation), and panel (c) shows experiment DTDB (with both Dark Target and Deep Blue MODIS retrievals in the assimilation).

Specific sites in China have also been selected in order to understand the model skill in both remote and urbanized regions that are particularly affected by Asian dust plumes. The agreement between the experiments and independent observations is generally better for AERONET stations than CARSNET stations with generally lower NMB and FGE, highlighting the fact that the arid Asian regions where some of the CARSNET stations are located are more challenging for the model to represent
20   correctly.

This can also be seen in 7 where the model is compared with the observations at several CARSNET stations over the whole month of March 2013. The increase in AOD corresponding to the passage of a storm on the 9th of March shown in
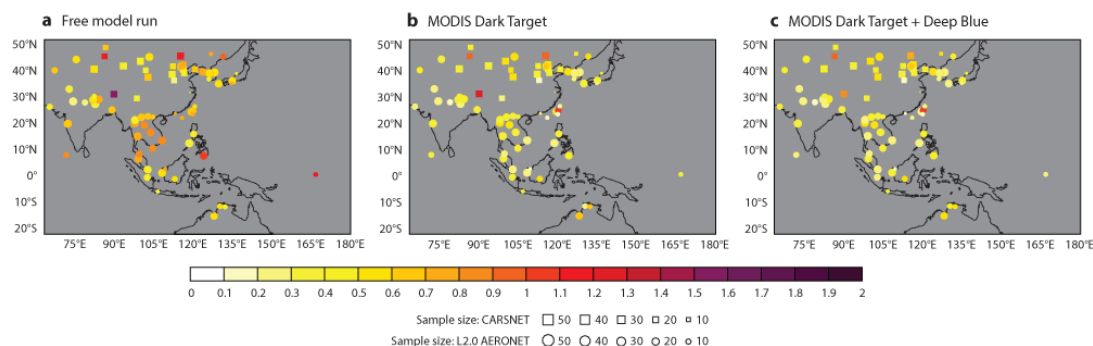
Figure 5. As in for figure 4 but for Fractional Gross Error.

figure 1 is evident in the ground-based CARSNET observations. The magnitude of the dust peak in the source region is best captured by the runs with assimilated Deep Blue AOD data, as shown in the time-series for Tazhong (39.0N-83.67E). The improvement coming from assimilation is especially felt downwind of the source regions, as seen for example in Shangri-La (28.03N-99.73E) to the South-East and Xilinhot (43.95N-116.12E) to the North-East.

4.2 Impact of the assimilation on the AD forecasts

In the previous subsection, results have been presented that show how assimilation of AOD satellite data from the MODIS retrievals brings beneficial improvements to the simulation of AOD within the ECMWF/CAMS system. The impact on the analysis is clearly shown in the improvement in the FB and FGE. The question that might arise at this point is whether the impact of the assimilated satellite data is only felt at the analysis time or whether it carries on to the subsequent forecast. To answer this question, the spatial data relative to FB shown in figure 4 are summarized using an histogram which shows the FB as a function of the number of AERONET and CARSNET sites. The upper panels show the histogram for the analysis time, whereas the lower panels show the same for the 48h forecast. Again, we can observe that the skill of the experiments with data assimilation is higher with respect to the control experiment. While this increased skill is higher at analysis time, it persists into the short-range forecast at 48h. ECMWF/CAMS forecasts are issued out to day 5. However, some users utilize of the forecast at day 2 for their applications. For example, for the management of solar power plants, it is the 48h aerosol forecast that is considered to plan the plant operations Schroedter-Homscheidt et al. (2013)). In these instances, a reduction in the forecast bias at day 2 is a welcome development. Moreover, experiment DTDB, which included both MODIS Dark Target and Deep Blue data, shows a slightly lower bias in the 48h forecast, indicating a beneficial impact of the additional observations close to the dust sources.

4.3 Comparisons with independent PM data

PM data were obtained for the month of March 2013 from CEPA for several stations in the Beijing area (see figure 9b). Comparisons between the observations and the model PM10 are shown in figure 9a. The data for all stations show a peak
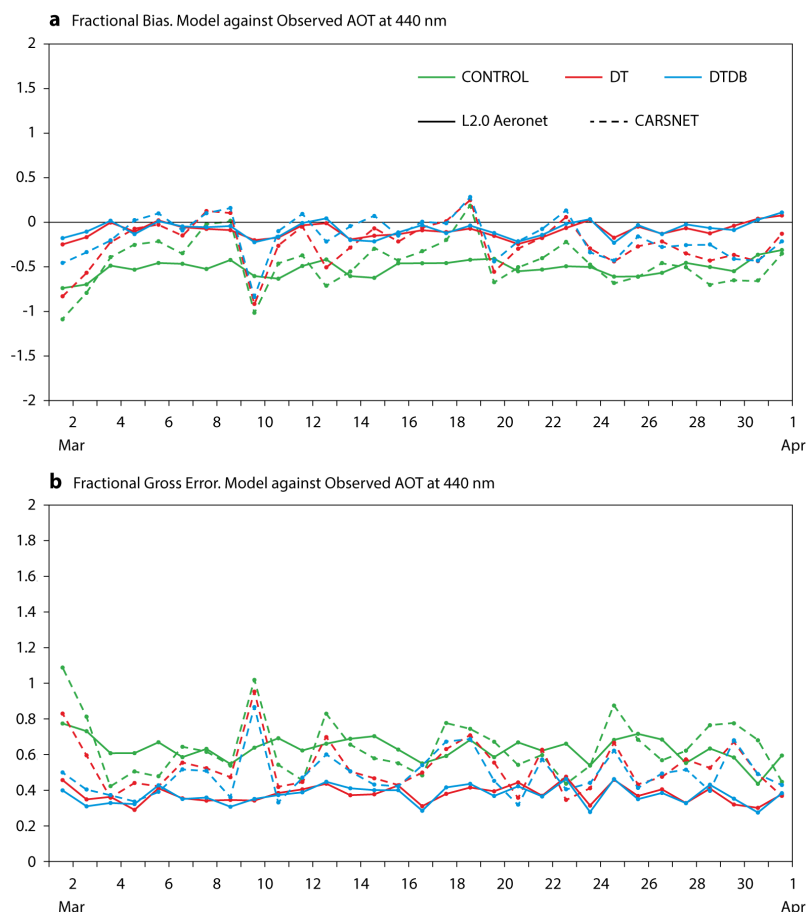
Figure 6. Time-series of Fractional Bias (top) and Fractional Gross Error (bottom) in AOD at 440nm averaged of the South-East Asia area (83 sites). Solid lines are relative to AERONET data whereas dotted lines are relative to CARSNET data. Green is experiment CONTROL, red is experiment DT and blue is experiment DTDB.

in PM10 (all particles with diameter smaller than 10 μm), corresponding to the passage of the dust front on March 9. The box-plot represent the histograms of hourly data obtained from the 11 air quality stations available in the Beijing municipality. Outliers are indicated with a dot. The coarse resolution of the ECMWF model means that all station points are included in the same grid box.

5   The model captures the front passage, with slight wrong timing, but good agreement in the values of PM10. It is important to notice that the coarse model resolution does not allow to resolve the fine details of the local pollution. However in situations dominated by large-scale synoptic events such as the case for the dust storm of March 9, the model can achieve a good degree of skill. This is what is seen for the experiment CONTROL in figure 9, although once again the experiments with assimilated satellite data draw closer to the observations. In particular the PM10 is increased in the DTDB experiment thanks to the

10   additional AOD data. The spurious secondary peak of March 10, not reported in the PM data, is slightly reduced in the DTDB
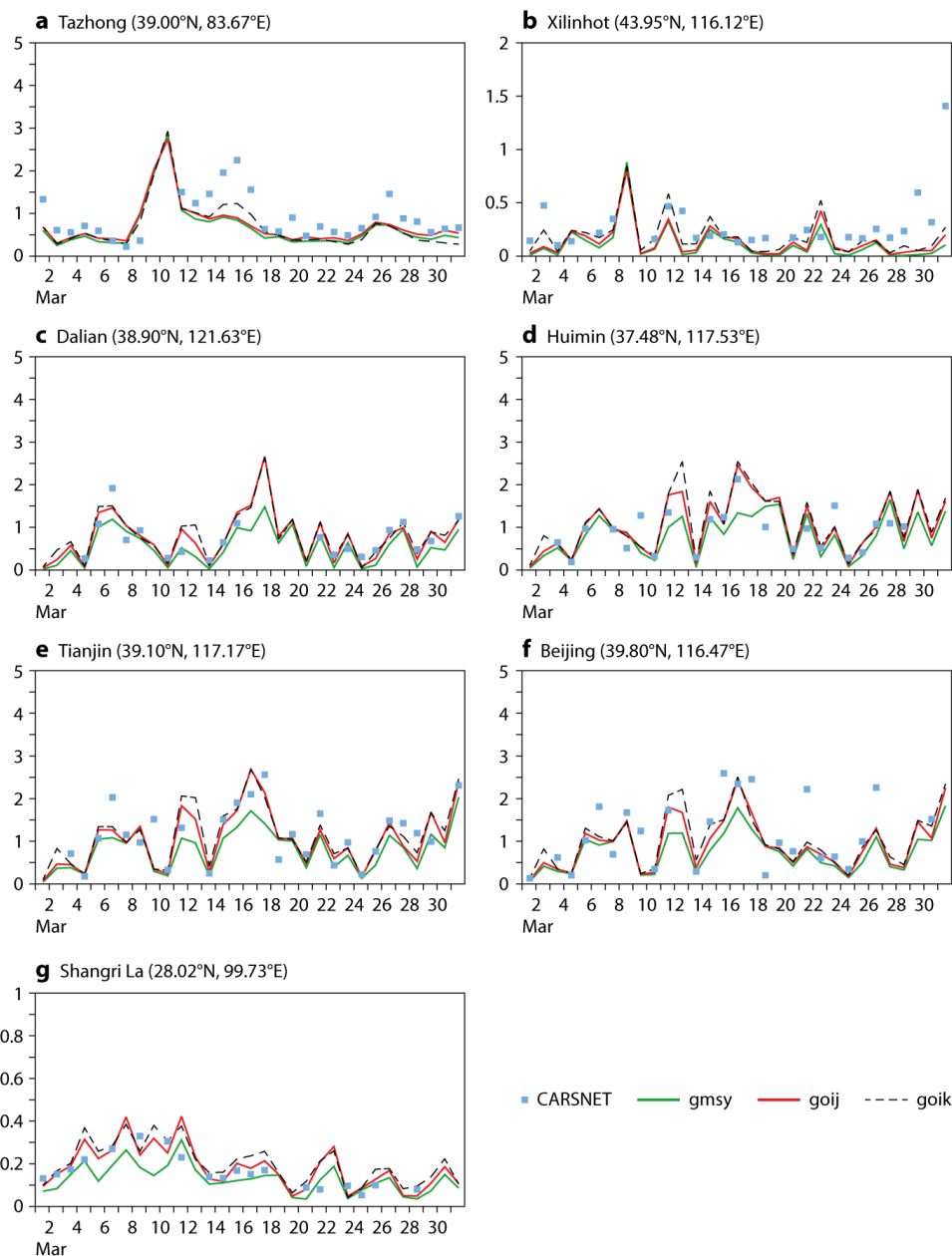
Figure 7. Comparison of CARSNET Aerosol Optical Depth data (blue squares) with model Aerosol Optical Depth at several CARSNET stations highlighted in 1. Green corresponds to experiment CONTROL, red to experiment DT, and gray to experiment DTDB. From top left to bottom right: Tazhong (39.0N-83.67E), Xilinhot (43.95N-83.67E), Dalian (38.90N-121.63E), Huimin (37.48N-117.53E), Tianjin (39.10N-117.17E), Beijing (39.80N-116.47E), Shangri-La(28.02N-99.73E).
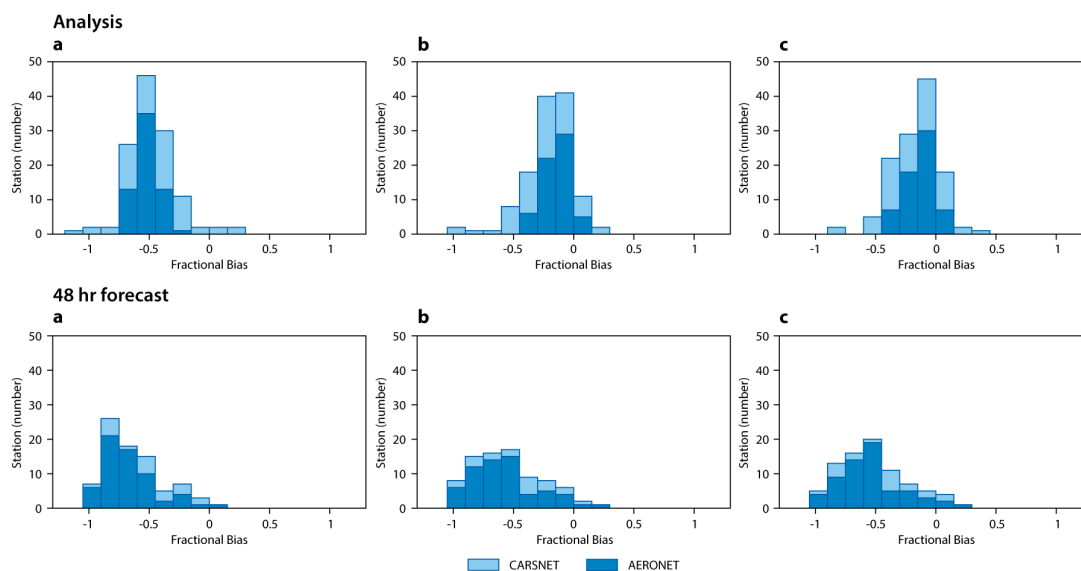
Figure 8. The histograms on the middle and bottom rows are constructed using data from all stations displayed in the map of figure 4 and are valid at the analysis and 48h forecast times, respectively. Panels (a) are relative to the experiment CONTROL, panel (b) to the experiment DT, and panels (c) to the experiment DTDB.

experiment. Once again this indicates the positive impact that the data have on the forecast of this type of events, even in situations of over-prediction.

5 Conclusions

The operational ECMWF/CAMS system was used to demonstrate the impact of assimilating satellite AOD data for an improved
5   prediction of Asian dust storms. Three experiments were conducted: one control experiment with no aerosol data assimilated, one experiment with only Collection 6 MODIS Dark Target AOD retrievals, which do not offer coverage over bright surfaces and one experiment with all available MODIS data including Deep Blue AOD retrievals.

Several concluding points can be learned from these experiments. Results confirm that assimilation of advanced satellite data is effective for improving the representation of desert dust distributions over Asia and subsequently for monitoring and
10 forecasting episodes. In particular, MODIS Deep Blue data are beneficial both in source regions (i.e. Tazhong) as well as downwind of desert areas (i.e. Xilinhot and Shangri-La). The fractional bias and the gross error with respect to independent AOD observations from the AERONET and CARSNET ground-based networks are lower in the assimilation experiments than in the control forecast with no assimilated aerosol data. Timeseries of FGE averaged over the South-East Asia region, reveal that in some extreme cases the FGE is reduced by as much as 60% in the experiment which includes all MODIS data (DTDB)
15 with respect to the experiment which has no aerosol data (CONTROL). The impact of the assimilated data is mainly felt at the analysis time but it persist into the 48h forecast.
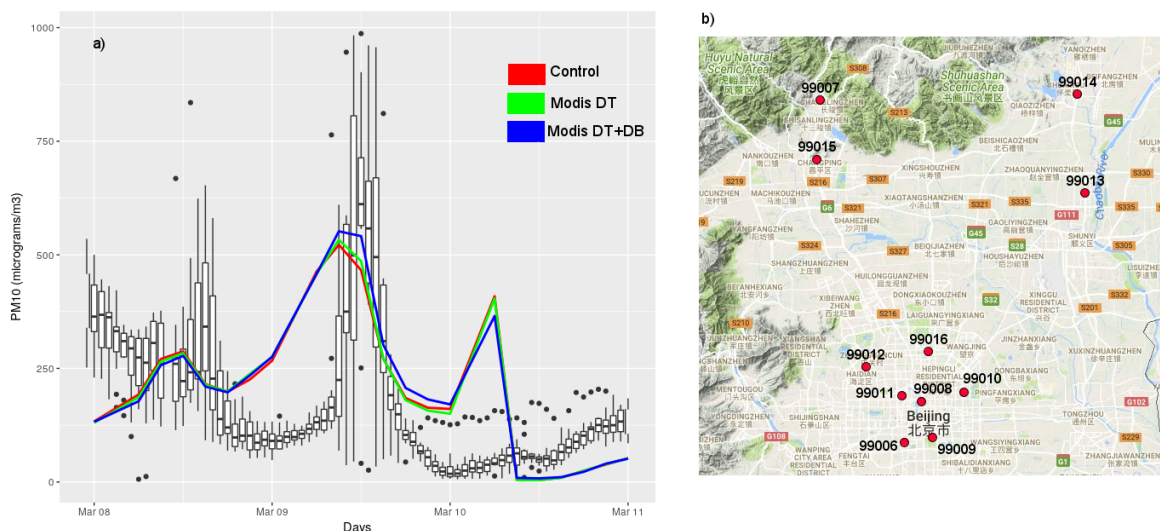
Figure 9. a) PM10 time series for the measurements recorded in the 11 stations available in the Beijing municipality and the simulations performed with the ECMWF model in the different configurations. b) location and identification code of the observation stations around the Beijing area.

Comparisons with PM data from the CEPA network for March 2013 in the Beijing area show that the model is skillful in predicting the passage of a dust front and the PM values are within the observed range. The assimilation experiments show, once more, a better overall agreement with the observations. In situations such as large dust events, the global model is able to capture the regional pollution patterns, despite the coarse resolution. This indicates that the global model fields can be used as

5 boundary conditions for regional air quality models at higher resolution, enhancing their performance in situations when part of the pollution may have originated via large-scale mechanisms.

These results also highlight the crucial importance of the verifying datasets to assess model skill and assimilation impact. CARSNET data offer unprecedented coverage over remote Asian dust regions, which are otherwise poorly observed. From the regional distribution maps (4) it is possible to see that CARSNET and AERONET stations over Asia are largely complementary.

10 Data availability in these regions both for assimilation and model evaluation and development is key to progress in further addressing the challenges of Asian dust prediction.

As part of CAMS, ECMWF is providing twice-daily forecasts of atmospheric composition (including desert dust) up to 5 days ahead, which are publicly available. These forecasts rely on assimilation of MODIS Collection 6.1 AOD (both Dark Target and Deep Blue data) as well as PMAP data. They have been shown to provide useful information and reliable boundary

15 conditions for local air quality applications in China and East Asia.

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5 (https://worldview.earthdata.nasa.gov/) operated by the NASA/Goddard Space Flight Center Earth Science Data and Information System (ESDIS) project. PM10 data were courtesy of the CEPA network.

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