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Forecasting the North African dust outbreak towards Europe in April 2011: a model intercomparison

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Abstract

In the framework of the World Meteorological Organisation's Sand and Dust Storm Warning Advisory and Assessment System, we evaluated the predictions of five state-of-the-art dust forecast models during an intense Saharan dust outbreak affecting Western and Northern Europe in April 2011. We assessed the capacity of the models to predict the evolution of the dust cloud with lead-times of up to 72 h using observations of aerosol optical depth (AOD) from the Aerosol Robotic Network (AERONET) and the Moderate Resolution Imaging Spectroradiometer (MODIS), and dust surface concentrations from a ground-based measurement network. In addition, the predicted vertical dust distribution was evaluated with vertical extinction profiles from the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP). To assess the diversity in forecast capability among the models, the analysis was extended to wind field (both surface and profile), synoptic conditions, emissions and deposition fluxes. Models predict the onset and evolution of the AOD for all analysed lead-times. On average, differences among the models are larger than differences among lead-times for each individual model. In spite of large differences in emission and deposition, the models present comparable skill for AOD. In general, models are better in predicting AOD than near-surface dust concentration over the Iberian Peninsula. Models tend to underestimate the long-range transport towards Northern Europe. Our analysis suggests that this is partly due to difficulties in simulating the vertical distribution dust and horizontal wind. Differences in the size distribution and wet scavenging efficiency may also account for model diversity in long-range transport.

1 Introduction

Desert dust, the largest contributor to the global aerosol burden after sea salt (Textor et al., 2006; Huneus et al., 2013), plays an important role in the climate system, the chemical composition of the atmosphere (e.g. Sokolik et al., 2001; Tegen, 2003;

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http://www.wmo.int/sdswas) and the International Cooperative for Aerosol Prediction (ICAP) initiative (http://icap.atmos.und.edu/). The SDS-WAS seeks to achieve a comprehensive, coordinated and sustained observations and modelling capacity for sand and dust storms (Terradellas et al., 2013). The overall aims are the monitoring of these events, increase the understanding of the dust processes and enhance the dust prediction capabilities. SDS-WAS is organized around two regional nodes, managed by Regional Centres (RC), namely the Northern Africa-Middle East-Europe Regional Centre (NAMEE) hosted by Spain (http://sds-was.aemet.es/), and the Asian Regional Centre hosted by China (http://www.sds.cma.gov.cn/). Each one of these nodes focuses on sand and dust storms within their region of action. More recently the ICAP (http://icap.atmos.und.edu/) was started. This international forum involves multiple centres delivering global aerosol forecast products and seeks to respond to specific needs related to global aerosol forecast evaluation (Benedetti et al., 2011). In contrast to SDS-WAS, this cooperative does not focus exclusively on dust but investigates forecast capabilities of all aerosol species at the global scale. Dust prediction is, however, an important component of the aerosol prediction activities.

Multiple studies have evaluated the model performance to simulate a given dust event (e.g. Pérez et al., 2006a; Heinold et al., 2007; Guerrero-Rascado et al., 2009; Kalenderski et al., 2013), yet only a few have analyzed in detail the model capabilities to predict them up to a few days ahead. Alpert et al. (2002) use the aerosol index (AI) of the Total Ozone Mapping Spectrometer (TOMS) to initialize a dust prediction system over Israel developed in the framework of the Mediterranean-Israeli Dust Experiment (MEIDEX). Zhou et al. (2008) evaluate an operational sand and dust storm forecasting system (CUACE/Dust) for East Asia, while Shao et al. (2003) present a real-time prediction system of dust storms in Northeast Asia. These forecasts successfully predict the temporal and spatial evolution of the dust plume, but little effort has been made to systematically examine the predictability of dust transport from Northern Africa to Europe.

and 72 h. A brief description of each of these datasets follows together with a general description of the models used in this work (Sect. 2.4).

2.1 Aerosol remote sensing

We used AOD observations at 550 nm from 21 Sun photometers operating within the AERosol RObotic NETwork (AERONET; Holben et al., 1998) whose locations are depicted in Fig. 1. We use quality-assured direct-sun data (Level 2.0) between 440 and 870 nm, which contain an uncertainty on the order of 0.01 for AOD under cloud-free conditions.

Quantitative evaluations of the modelled dust AOD are conducted for dust-dominated conditions; i.e. when the Ångström exponent (AE) is less or equal to 0.75 (Basart et al., 2009). All data with AE larger than 1.2 are associated to fine anthropogenic aerosols and are considered free of dust. Values of AE between 0.75 and 1.2 are associated with mixed aerosols and are not included in the analysis. The AOD at 550 nm is derived from data between 440 and 870 nm following the Ångström's law. Because AERONET data are acquired at 15 min intervals on average, all measurements within ± 90 min of the models' outputs are used for the 3 hourly evaluation.

In addition to ground-based observation, we qualitatively compare the modelled dust AOD to satellite-retrieved aerosol distribution from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite. We use daily data from the MODIS Level 3 aerosol products from collection 5.1 at $1^\circ \times 1^\circ$ horizontal resolution. The MODIS algorithm over land produces data only for low ground reflectance (i.e. over dark surfaces) leaving dust aerosol over bright deserts undetected (Remer et al., 2005). To evaluate the models over deserts we combine the data with the MODIS Aqua Deep Blue product, which provides information over arid and semi-arid areas by employing radiances from the blue channels to enhance the spectral contrast between surface and dust (Hsu et al., 2004, 2006).

In order to examine the predicted vertical profile of dust aerosol, data from the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor on board the

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are the sole models to present northerly wind component from 18:00 UTC on 4 April until 06:00 UTC on the next day. Although observations show north-easterly, this only at 06:00 and 21:00 UTC on 4 April. Furthermore, no model reproduces the strong winds at 03:00 UTC on 4 April, neither in terms of magnitude nor in direction. Interestingly, MERRA reanalysis shows similar difficulties to reproduce the observations as the forecasts.

We examine now the model performance to forecast the vertical profile of horizontal winds measured by two daily radiosondes (noon and midnight) at Bachar (2.25° W, 31.5° N) in Algeria (Fig. 11) close to the dust source of this event (Fig. 1). The closest model gridbox to the station is considered in this analysis. Two different regimes can be identified from the observed profiles. The dust-emitting regime until 7 April is characterized by almost constant southerlies above 1 km a.g.l. and easterlies near the surface in agreement with the cyclone (Sect. 4.4). The wind speeds generally increase until 5 April and decrease thereafter. Maxima in wind speed around 30 ms⁻¹ on 5 April are reached in two layers centred approximately around 1.5 and 4 km. The subsequent relatively calm regime is characterized by weaker winds and stronger variability in wind direction with height and time. The following analysis will focus on the first regime given its role in the emission and northward transport of dust during the event.

All models simulate the dominant southerlies at elevated levels but they do not reproduce the easterlies close to the surface (Fig. 11). Furthermore, most models represent the two maxima in wind speed, yet the maximum around 4 km a.g.l. is weaker and found at higher levels than in the observations. The observed wind maximum between 1 and 2 km a.g.l. is poorly forecasted. Except in ECMWF/MACC, this maximum is forecasted 12 h prior to the observations. In addition, the performance to reproduce the depth of the layer with strong winds and its duration varies amongst models. The onset is well reproduced by all models and the strong southerlies agree with observations above 3 km, but below this height, most models terminate the strong winds one day earlier compared to the observations. Lead times of 48 h show no large impact for the other

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tude of the dust layer as suggested by CALIOP observations. We note however, that CALIOP may overestimate the aerosol extinction coefficient in layers with significant mixture of mineral dust and marine aerosols due to an overestimation of the lidar ratio (Cuevas et al., 2014). Nevertheless, both of the before mentioned factors (vertical structure of horizontal wind and vertical dust propagation) combined could contribute to the reduced northward dust transport to Birkenes in the models; dust particles do not reach layers of strong winds responsible for the northward transport.

The models show, all in all, similar performance to forecast AERONET AOD. In general no model outperforms the other in all statistics and for both variables (AOD and surface concentration) and the inter-model spread is larger than the change in forecast skill with lead-time. While for the near-surface concentration of dust the NMMB/BSC-Dust presents the best performance in term of all statistics, for AOD the best performing model depends on the region and forecast lead-time. We recall the reader that for analysis with AERONET data, stations were grouped into southern (SE), central (CE) and northern Europe (NE), whereas for surface concentration stations were not grouped but considered as part of southern Europe. Furthermore most models present better RMS and mean bias in CE. This suggests that errors are large both close to dust sources and in long-distance transport. In addition, NE presented in some cases better statistics than SE. The reasons for this has not been examined in detail, but could be a consequence of the low AOD in NE including non-dust situations, i.e. the models successfully reproduce the dust free days in northern Europe. For near-surface dust concentration, the different forecast lead-times also show similar performance for each model. As for AOD, overall the difference between models is larger than the differences between lead-times. We note however that these results correspond to only one event and the number of stations used in this statistical analysis is small (21 stations for AOD and 24 for dust surface concentration) with only a few days considered. Therefore, the statistical significance of these results needs to be explored considering multiple events before drawing generalized conclusions.

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We use the mean normalized gross errors (MNGE) to assess the difference between the performance to reproduce AOD and near-surface concentration. This statistic measures the relative difference to the observations and allows comparing two variables with different magnitudes. Consistent with the difficulties of models to reproduce the vertical dust distribution, quantitative assessment of the model performance in AOD and near-surface dust concentration show that models have a better forecast skill for the former independent of the forecasting lead times and station; all show smaller MNGE for the AOD (Table 6). Furthermore, the model diversity to forecast near-surface dust concentration, indicated by the range of MNGE between the models, is much larger than the corresponding range in AOD forecast skill.

In spite of the large model diversity in magnitude and spatial distribution of the emissions and deposition, models present comparable performance when simulating AOD over Northern Africa and Europe. Although this feature can be likely attributed to the practice in model development using AOD values to tune dust simulations, other reasons cannot be excluded. The AOD depends on both, burden and size distribution of dust particles. Therefore, biases in AOD, in particular in the source region, can be associated to biases in the net fluxes and/or to misrepresentation of the size distribution (Huneeus et al., 2011). In addition, definition of optical parameters is also relevant to determine the scattering efficiency of dust particles in a model, and thus AOD. The present study has focused on the forecast skill of the dust lifecycle (i.e. emission, transport and deposition) of a given event from different models, but has not examined the role of size distribution nor definition of optical parameters in the forecast performance. We suggest that future intercomparison studies examining the model performance to reproduce the dust lifecycle include explicitly the size distribution in their analysis and comparisons against observations allowing to conclude on the performance to reproduce it (e.g. Angström exponent). In addition, the comparison of definition of optical parameters between the different models should also be incorporated.

6 Conclusions

As part of the WMO SDS-WAS five state-of-the-art dust forecast models were examined in their performance to predict the onset, evolution and termination of an intense Saharan dust outbreak towards Western Europe and Scandinavia between 5 and 11 April 2011. The models were assessed in their capacity to predict the evolution of the AOD and near-surface dust concentration with a lead-time of up to 24, 48 and 72 h. Our results underline that the choice of model has a larger impact on the forecast skill than the lead-time. To identify possible reasons for the different model performance, the evaluation was extended to profiles of extinction coefficient measured by CALIOP, wind profiles from one radio sounding station in the source region, 10 m winds observed at meteorological stations and synoptic conditions compared to MERRA reanalysis.

The models are successful in predicting the onset and evolution of the dust cloud in terms of AOD for all three analyzed lead-times, namely 24, 48 and 72 h. All models reproduce the main features of the evolution of both AERONET and MODIS observations. The main differences are the magnitude of the simulated AOD; while AOD at the source region is both over and underestimated by the models, the AOD in northern Europe is underestimated by all models. The over/under estimation of AOD close to the source suggests that emissions might be over/under estimated by the models but a misrepresentation of the size distribution cannot be excluded as a source of this bias. The underestimated AOD over northern Europe reveals that all models underestimate the northward transport of dust, in particular by those models overestimating the AOD in the source region. This underestimation of northern dust transport might indicate difficulties of the models to represent removal processes or synoptic conditions affecting the transport. Comparison against wind profiles and observations of vertical dust distribution showed that models simulate too shallow dust layers, weaker horizontal winds and layers with maximum wind at higher altitudes than observed. The combination of these factors might explain why not enough dust is transported northward.

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clude on emissions biases due to biases in AOD. However, the impact of the scattering efficiency on the forecast skill has not been addressed. The AOD depends on burden and size distribution, but definition of optical parameters is also relevant to determine the scattering efficiency of dust particles in a model. We leave this investigation for future studies.

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Table 1. Summary of the main features of each model included in the present contribution.

Dust model	Domain	Meteo. initial fields	Texture and vegetation type datasets	Radiation Interaction with dust	Horiz./Vert. resolution	Dust Emission Scheme	Surface wind speed for dust emission	Threshold friction velocity	Dry and wet deposition	Transport size bins
BSC-DREAM8b	Regional	NCEP	STATSGO-FAO 5 min USGS 1 km	P06	0.3° × 0.3° 24 σ -layers	S93	viscous sublayer	B41 F99	Z01 N01	8 bins 0.1–10 μ m
NMMB/BSC-Dust	Regional/	NCEP	STATSGO-FAO 5 min USGS 1 km	no	0.25° × 0.25° 40 σ -layers	W79-MB95	viscous sublayer	IW82 F99	Z01 BMJ	8 bins 0.1–10 μ m
ECMWF/MACC	Global	ECMWF	USGS 1 km	no	1° × 1° 91 layers	GP88-G01	10 m gusts from 10 m wind field	G01	B02 GC86	3 bins 0.03–20 μ m
MetUM TM	Global	MetUM	FOA 2009	no	0.35° × 0.23° 70 layers	W01, W11	10 m wind field	B41 F99	W01	2 bins 0.1–10 μ m
DREAM8-NMME	Regional	ECMWF	STATSGO-FAO 5 min USGS 1 km	no	0.2° × 0.2° 28 σ -layers	S93	viscous sublayer	B41 F99	Z01 N01	8 bins 0.1–10 μ m

The codes denote the following references. B02: Boucher et al. (2002); B41: Bagnold (1941); F99: Fécan et al. (1999); G01: Ginoux et al. (2001); GC86: Giorgi and Chameides (1986); GP88: Gillette and Passi (1988); IW82: Iversen and White (1982); MB95: Marticorena and Bergametti (1995); S93: adapted Shao et al. (1993); P06: Pérez et al. (2006b); White (1979); Z01: Zhang et al. (2001); N01: Nickovic et al. (2001); W01: Woodward (2001); W11: Woodward (2011).

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Table 2. Root mean square (RMS) error quantifying the performance to reproduce AERONET total AOD for each model. The statistics are computed for stations in Southern, Central and Northern Europe (Fig. 1), considering the period between 5 and 11 April. We note that for all models the dust AOD was used.

	Southern Europe			Central Europe			Northern Europe		
	24	48	72	24	48	72	24	48	72
DREAM8-NMME	0.18	0.21	0.18	0.13	0.14	0.15	0.19	0.19	0.20
BSC-DREAM8b	0.20	0.20	0.19	0.17	0.17	0.16	0.32	0.33	0.31
ECMWF/MACC-Dust	0.18	0.17	0.24	0.15	0.14	0.14	0.12	0.18	0.12
NMMB_BSC	0.19	0.21	0.23	0.17	0.16	0.17	0.23	0.26	0.25
MetUM	0.12	0.14	0.14	0.15	0.16	0.15	0.18	0.18	0.24

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Table 3. Same as Table 2 but for mean bias (MB).

	Southern Europe			Central Europe			Northern Europe		
	24	48	72	24	48	72	24	48	72
DREAM8-NMME	-0.10	-0.10	-0.09	-0.06	-0.06	-0.06	-0.06	-0.07	-0.06
BSC-DREAM8b	-0.09	-0.10	-0.08	-0.10	-0.10	-0.08	-0.22	-0.22	-0.20
ECMWF/MACC-Dust	0.09	0.07	0.08	-0.07	-0.07	-0.06	-0.06	-0.07	-0.05
NMMB_BSC	-0.11	-0.11	-0.08	-0.10	-0.10	-0.10	-0.13	-0.15	-0.11
MetUM	0.04	0.06	0.02	-0.06	-0.06	-0.04	-0.03	-0.04	-0.03

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Table 4. Same as Table 2 but for Pearson correlation coefficient (R).

	Southern Europe			Central Europe			Northern Europe		
	24	48	72	24	48	72	24	48	72
DREAM8-NMME	0.76	0.62	0.74	0.50	0.42	0.21	0.74	0.75	0.67
BSC-DREAM8b	0.66	0.66	0.66	0.17	0.11	0.04	0.64	0.63	0.48
ECMWF/MACC-Dust	0.83	0.81	0.69	0.29	0.37	0.41	0.91	0.78	0.91
NMMB_BSC	0.72	0.64	0.61	0.14	0.24	0.11	0.76	0.54	0.47
MetUM	0.89	0.87	0.81	0.20	0.12	0.17	0.72	0.73	0.43

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Table 5. Root mean square (RMS) error, mean bias and correlation quantifying the performance to reproduce dust surface concentration in the Iberian Peninsula. Figure 1 illustrates the location of the stations used in the computation of the statistics. We note that for the models, the total dust surface concentration was used.

	RMS			Mean Bias			Correlation		
	24	48	72	24	48	72	24	48	72
DREAM8-NMME	15.9	17.1	16.6	-0.4	-2.1	-1.8	0.22	0.13	0.15
BSC-DREAM8b	28.6	27.3	28.8	12.0	11.7	12.7	0.38	0.41	0.35
ECMWF/MACC-Dust	28.1	28.9	28.6	20.2	20.7	20.1	0.36	0.34	0.47
NMMB_BSC	16.8	16.0	15.2	-9.9	-9.6	-7.6	0.46	0.55	0.53
MetUM	147.1	126.5	125.1	110.7	99.0	100.4	0.29	0.35	0.38

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Table 6. Mean normalized gross error quantifying the performance to reproduce AERONET total AOD in Southern Europe and surface concentration for each model and each lead-time forecast. We note that for the models, the dust AOD and dust total surface concentrations were used.

	AOD			Sfc. Conc.		
	24	48	72	24	48	72
DREAM8-NMME	0.35	0.37	0.34	1.06	0.99	0.98
BSC-DREAM8b	0.41	0.44	0.43	1.91	1.86	1.88
ECMWF/MACC-Dust	0.50	0.50	0.62	2.28	2.36	1.96
NMMB_BSC	0.45	0.48	0.48	0.75	0.67	0.71
MetUM	0.34	0.39	0.38	9.75	8.70	8.78

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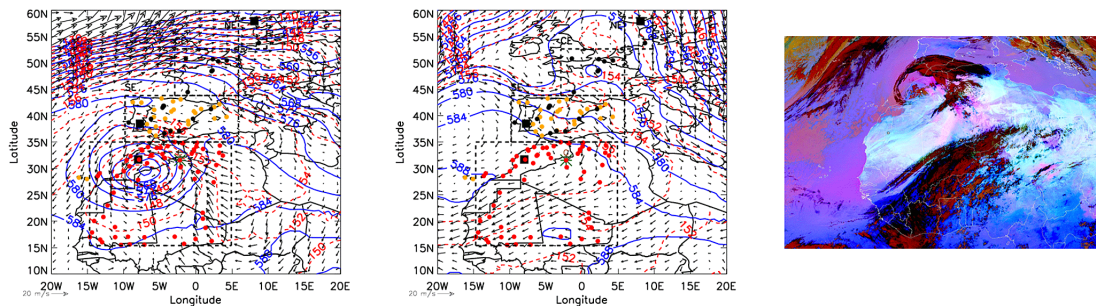


Figure 1. Geopotential height at 500 hPa (blue lines) and 850 hPa (red lines) for 5 and 10 April 2011 and wind field at 850 hPa. AERONET (orange), surface concentration (black), surface wind (green) and radiosounding (brown) stations used in this study are presented. Southern, Central and Northern Europe (SE, CE and NE, respectively as the dashed black squares) regions used in the statistical analysis are illustrated, as well as the region used to produce the emission time series in Fig. 5. The MSG/RGB dust product of the “spinning enhanced visible and infrared imager” (SEVIRI) shows the cloud band of the cyclone (red) and dust aerosol (pink) of the dust event over Northwest Africa on 5 April 2011 at 12:00.

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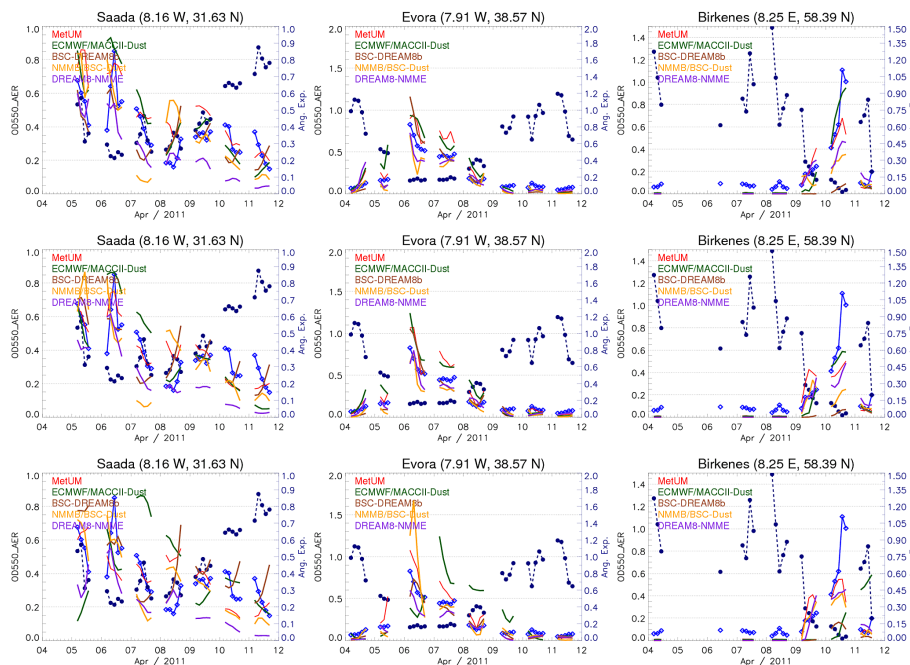


Figure 2. Total AOD at 550 nm at three selected sites from the AERONET network (blue line) and 24 (first row), 48 (middle row) and 72 h (bottom row) forecast of the model MetUM (red), ECMWF/MACC (green), BSC-DREAM8b (brown), NMMB/BSC-Dust (orange) and DREAM8-NMME (purple) are illustrated. The Angström exponent (dark blue dots) from the AERONET network at the three selected sites is also included. Angström exponent < 0.75 indicate the dominance of desert dust.

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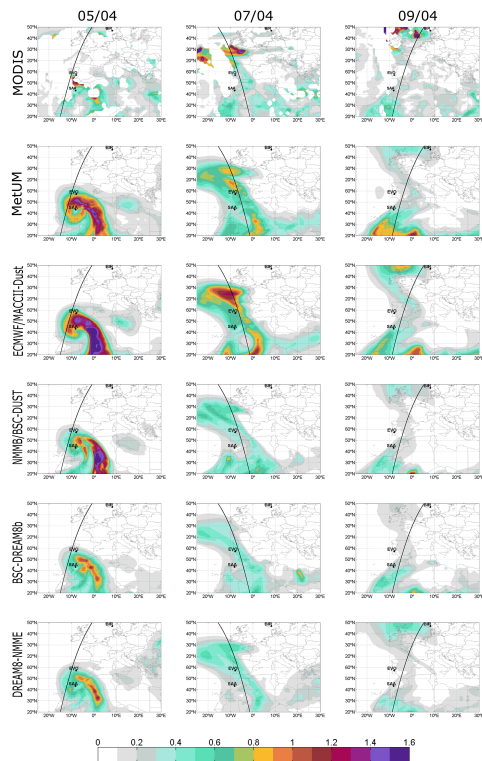


Figure 3. Maps of daily total AOD at 550 nm from MODIS (first row) and corresponding 24 h forecast of models MetUM (second row), ECMWF/MACC (third row), NMMB/BSC-DUST (fourth row), BSC-DREAM8b (fifth row) and DREAM8-NMME (sixth row) for 5 (first column), 7 (second column) and 9 (third column) April 2011. Corresponding maps for all days between 4 and 11 April are given in Fig. S01 in the Supplement and 48 and 72 h forecast maps are provided in Figs. S02 and S03. The three AERONET site show in Fig. 2 (black dots) and the CALIPSO orbits (black lines) are also shown.

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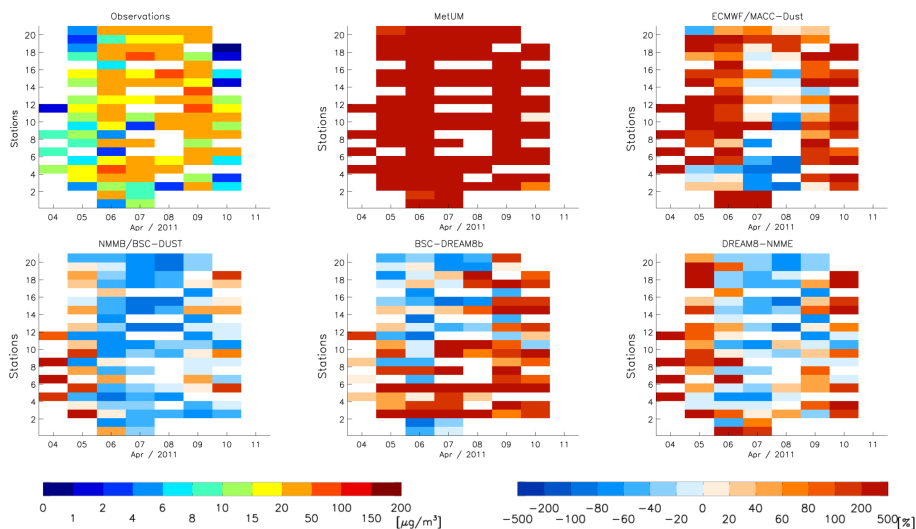


Figure 4. Daily measured surface concentration [$\mu\text{g m}^{-3}$] and normalized bias of corresponding 24 h forecast surface concentration [%] at stations illustrated in Fig. 1. Each row corresponds to one of the stations. Stations are ordered from south to north and white colour corresponds to days without measurements. Corresponding 24 h forecast model surface concentration are illustrated in Fig. S04 in the Supplement and the 48 and 72 h of normalized bias of forecasted surface concentration are provided in Figs. S05 and S06.

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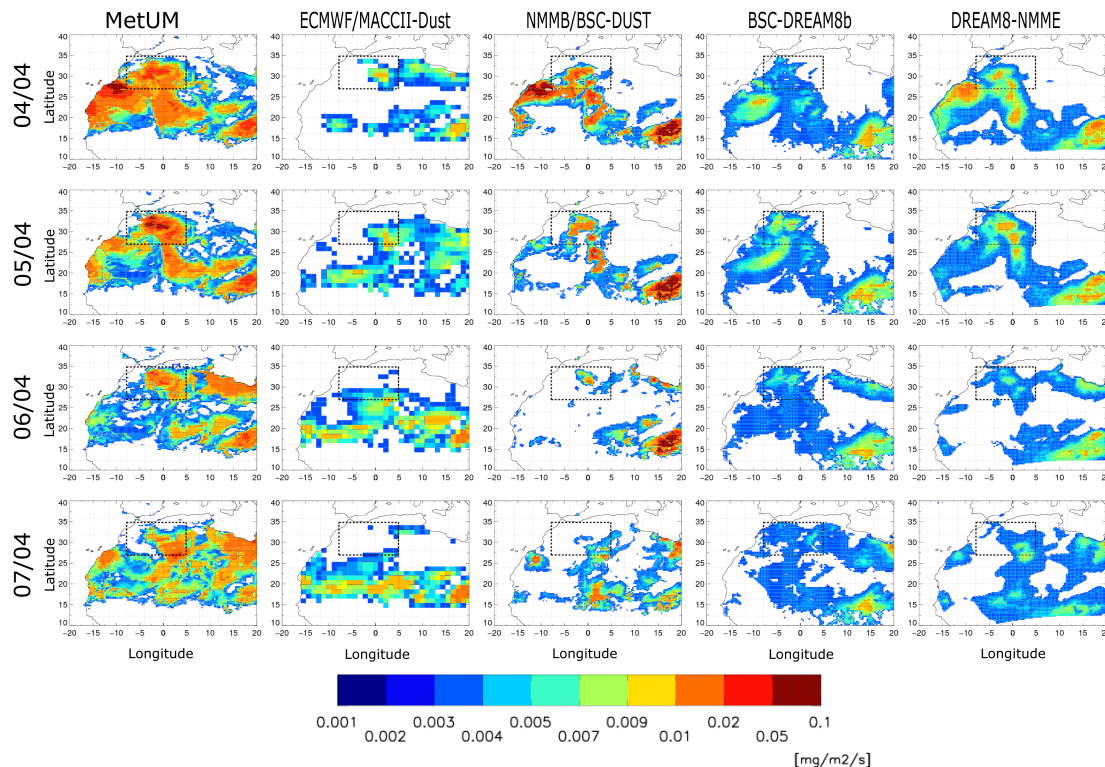


Figure 5. Forecasted daily average emission with 24 h lead-time for the models MetUM (first column), ECMWF/MACC (second column), NMMB/BSC-DUST (third row), BSC-DREAM8b (forth column) and DREAM8-NMME (fifth row). Dashed box illustrates region used in the time series emissions illustrated in Fig. 6.

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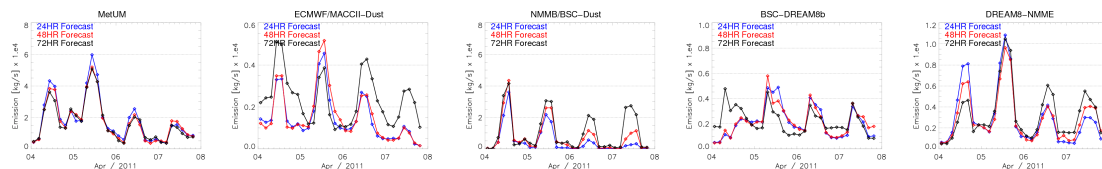


Figure 6. Time series of 3 hourly emissions from models MetUMTM, ECMWF/MACC, NMMB/BSC-Dust, BSC-DREAM8b and DREAM8-NMME with 24, 48 and 72 h lead-time (blue, red and black respectively).

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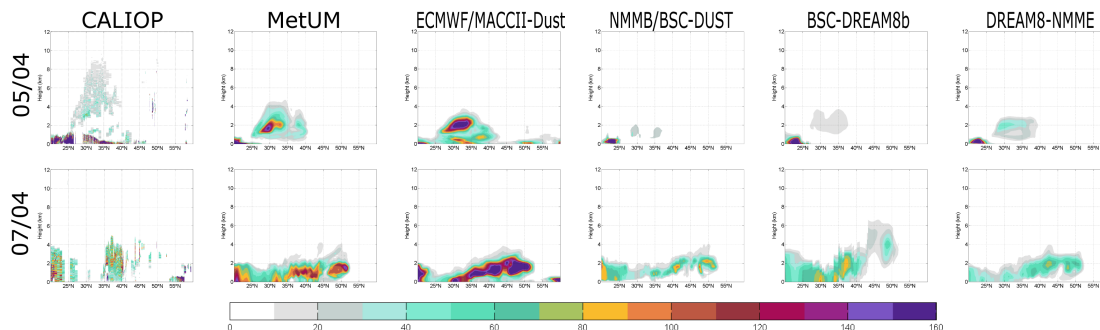


Figure 7. Profiles of measured total extinction coefficient at 532 nm from the CALIOP instrument onboard of the CALIPSO satellite and 24 h forecasted dust extinction coefficient profiles at 532 nm from models MetUM, ECMWF/MACC, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME. Conditions are presented for 5 (upper row) and 7 (lower row) April. Overpass of the satellite in each case is illustrated in Fig. 3. Corresponding forecasted model profiles for 48 and 72 h lead times are illustrated in Figs. S10 and S11, respectively.

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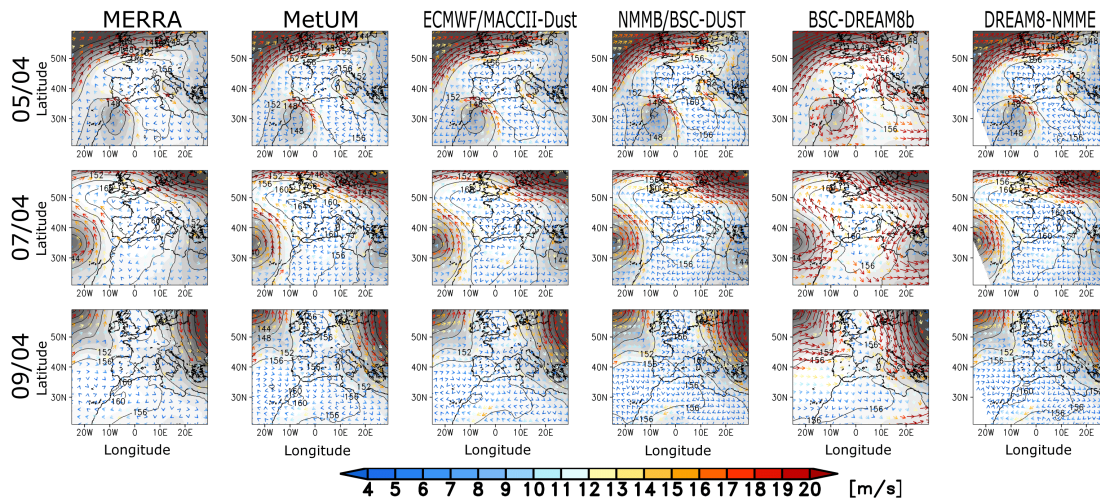


Figure 8. The geopotential height (contours) and wind speed stream lines at 850 hPa on 5 (first row), 7 (second row) and 9 (third row) April 2011 at 12:00 UTC from MERRA reanalysis and the 24 h forecast from MetUM, ECMWF/MACC, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME (from left to right).

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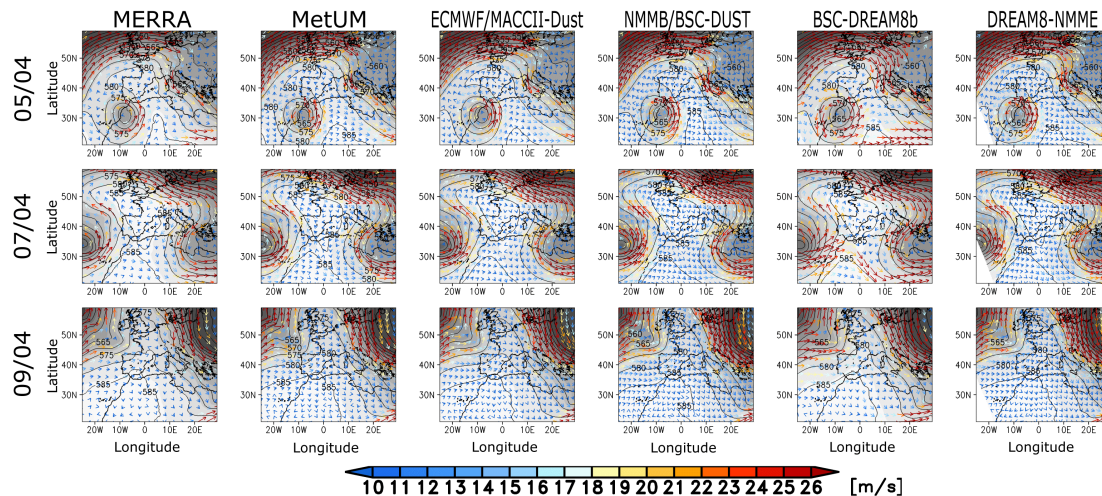


Figure 9. Same as Fig. 8 but for 500 hPa.

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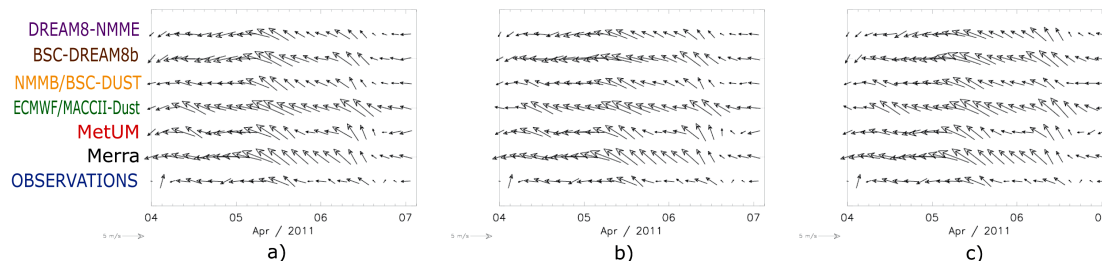


Figure 10. Time series of near-surface wind speeds in dust source region. Three-hourly values of the 10 m-wind speed from observations and re-analysis (MERRA), global models and regional models for the period 4 April 2011 to 7 April 2011 with **(a)** 24 h lead time, **(b)** 48 h, and **(c)** 72 h. Observations are averaged over the region illustrated in Fig. 1. The 10 m-winds from the models are averaged over the grid boxes enclosing the observation station.

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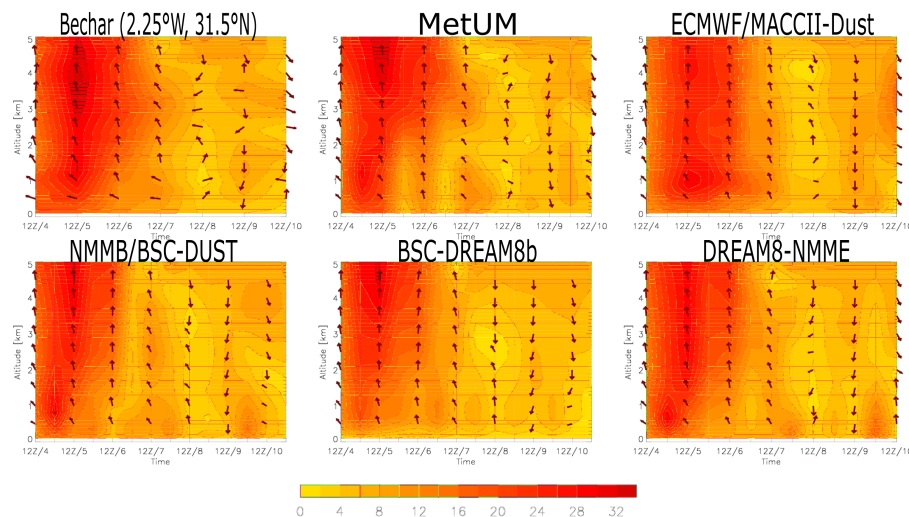


Figure 11. Profiles of measured wind speed (m s^{-1} , filled contours) and direction (vectors, first column) between the 4 and 10 April from radiosounding at Bachar (2.25° W , 31.5° N ; first row) and the corresponding 24 h forecast of models MetUM, ECMWF/MACC, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME.

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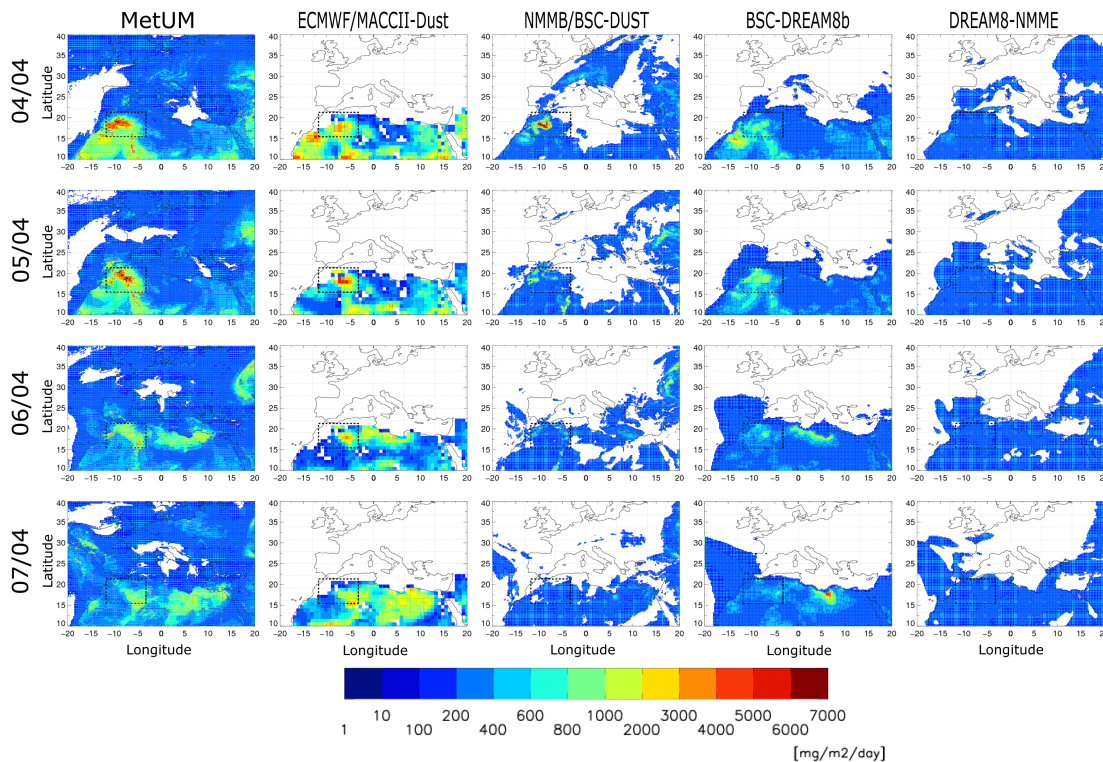


Figure 12. Total accumulated forecasted daily deposition with 24 h lead time for the models MetUM, ECMWF/MACCI2-Dust, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME (from left to right).