



HAL
open science

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

N. Huneus, S. Basart, S. Fiedler, J. -J. Morcrette, A. Benedetti, J. Mulcahy, E. Terradellas, C. Pérez García-Pando, G. Pejanovic, S. Nickovic, et al.

► **To cite this version:**

N. Huneus, S. Basart, S. Fiedler, J. -J. Morcrette, A. Benedetti, et al.. Forecasting the North African dust outbreak towards Europe in April 2011: a model intercomparison. Atmospheric Chemistry and Physics Discussions, 2015, 15, pp.26661-26710. 10.5194/acpd-15-26661-2015 . hal-04114743

HAL Id: hal-04114743

<https://hal.science/hal-04114743>

Submitted on 8 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

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

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

¹⁰National Hydrometeorological Service, Belgrade, Serbia¹¹Institute of Environmental Assessment and Water Research, Spanish Research Council, Barcelona, Spain¹²Institute for Atmospheric and Climate Science, ETH, Zürich, Switzerland¹³Norwegian Meteorological Institute, Oslo, Norway¹⁴Izaña Atmospheric Research Center, State Meteorological Agency of Spain (AEMET), Santa Cruz de Tenerife, Spain¹⁵Environmental Modelling Laboratory, Technical University of Catalonia, Barcelona, Spain¹⁶Geological Survey of Spain (IGME), Zaragoza, Spain^anow at: Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, Karlsruhe, Germany^bnow at: Max-Planck Institute for Meteorology, Hamburg, Germany^cnow at: Laboratoire de Météorologie Dynamique, IPSL, CNRS/UPMC, Paris, France

Received: 4 August 2015 – Accepted: 24 August 2015 – Published: 1 October 2015

Correspondence to: N. Huneus (nhuneus@dgf.uchile.cl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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;

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Forecasting the
North African dust
outbreak towards
Europe in April 2011**N. Huneus et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

<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.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The present work is done within the framework of the SDS-WAS NAMEE node. This RC gathers and coordinates the exchange of forecasts produced by different dust models and conducts regular model inter-comparison and evaluation within its geographical scope. We examine the performance of five state-of-the-art dust forecast models to predict the intense Saharan dust outbreak transporting dust over Western Europe to Scandinavia between 5 and 11 April 2011. Studying a single dust event allows to investigate the model skill in predicting the approach of a dust event with a high temporal resolution of a few hours. Each model is compared against a set of observations, namely dust surface concentration, extinction profiles, aerosol optical depth (AOD) at 550 nm, wind at 10 m a.g.l. and profiles of the horizontal wind. This comprehensive inter-comparison of the models reveals strengths and weaknesses of individual dust forecasting systems and provides an assessment of uncertainties in simulating the atmospheric dust cycle at high temporal resolution. The paper is structured as follows. In Sect. 2 the observational data used for the evaluation and the models considered in this work are introduced. In Sect. 3 we describe the intense dust event selected for this study. Results are shown in Sect. 4 and their discussion is provided in Sect. 5. Our conclusions are described in Sect. 6.

2 Data and models

The model evaluation focuses on the days of the event, i.e. from 5 to 11 April, and uses data over the North African source region and Europe. Figure 1 shows the region of study along with the locations of the observation stations used. The models are evaluated against aerosol optical depth (AOD), vertical profiles of aerosol backscatter and extinction coefficient (Sect. 2.1), dust surface concentrations (Sect. 2.2), wind speed and other meteorological variables relevant for the event (Sect. 2.3). We conduct a statistical analysis, based on 3 hourly data whenever possible and daily data otherwise and we analyse the models' performance to predict the event with lead-times of 24, 48

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) is used. CALIOP is a standard dual-wavelength (532 and 1064 nm) backscatter lidar operating at a polarization channel of 532 nm. It measures high-resolution (1/3 km in the horizontal direction and 30 m in the vertical direction) profiles of the attenuated backscatter of aerosols and clouds at 532 and 1064 nm along with polarized backscatter in the visible channel (Winker et al., 2009). We use here the version 3.01 of the Level 2 aerosol backscatter and extinction product at 532 nm (i.e. CAL_LID_L2_05kmAPro-Prov-V3-30). This product has a horizontal resolution of 5 km and a vertical resolution of 60 m in the tropospheric region up to 20 km and 180 m above. We focus on 5 and 7 April. The model profiles are derived applying a bilinear interpolation to the four closest model grid points to the CALIOP overpass. We also applied a linear temporal interpolation between the two closest 3 hourly outputs to the time of the CALIOP observation.

2.2 Dust surface concentration

We also compare the forecasts against daily surface African dust concentration of PM_{10} for a number of Southern European regional background (RB) environments. Pey et al. (2013) created a database with daily desert dust PM_{10} concentrations from 2001 to 2011. We use here 24 stations of this dataset (Fig. 1). Daily contributions of African dust to PM_{10} were obtained by subtracting the daily RB level from the PM_{10} concentration of the day of the event (Escudero et al., 2007). The RB concentration is derived from application of the monthly moving 40th percentile to the PM_{10} time series after a prior extraction of the days with African dust.

2.3 Wind data

National Meteorological Services operate networks of manned and automated weather stations that regularly report atmospheric conditions following WMO standards. In particular, surface stations report synoptic observations every 3 or 6 h through the WMO's Global Telecommunications System. These observations, in combination with upper-

3 Dust event

The African dust outbreak affected Europe between 5 and 11 April 2011. On 4 April, an upper level trough approached Northwest Africa from the west. Advection of positive vorticity and the flow interaction with the Atlas Mountains favoured cyclogenesis in the mountain lee (not shown). On 5 April, the cyclone had deepened over the southern Moroccan-Algerian border causing strong winds of more than 20 ms^{-1} at 850 hPa. The associated near-surface winds produced dust mobilization over Algeria (Fig. 1).

The emitted dust aerosol was subsequently transported northwards and reached the Iberian Peninsula following the cyclonic flow (not shown). On 6 and 7 April, a ridge of high pressure over France and a cyclone west of the Azores Islands caused southeasterly winds of up to 17 ms^{-1} at 850 hPa to the west of the Iberian Peninsula that advected the dust plume towards the Atlantic Ocean. High pressure built and strengthened over the Iberian Peninsula and Northwest Africa between the 8 and 9 April. The resulting southerly winds over the Atlantic transported the dust-laden air towards Great Britain. 10 and 11 April were characterized by a ridge over West Europe with strong south-westerly winds over Great Britain, which advected the more diffused dust cloud towards Scandinavia (Fig. 1b).

4 Results

4.1 Dust transport: AOD and PM_{10}

The northward transport of dust was examined by comparing model AOD forecasts with AERONET measurements at three stations located along the path of the dust cloud (Fig. 2) and daily AOD maps from MODIS (Figs. 3 and S01–S03 in the Supplement). The three AERONET stations are Saada (31.63° N , 8.16° W) in Morocco close to the dust source, Evora (38.57° N , 7.91° W) in Portugal, and Birkenes (58.39° N , 8.25° E) in Norway (Fig. 1, black squares). The AOD in Saada peaked on 6 April and a second and

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



smaller maximum was observed on 9–10 April (Fig. 2). The latter peak corresponds to a dust plume that did not affect the Iberian Peninsula and is therefore omitted in our discussion. The time series in Evora and Birkenes feature sharp AOD increases during the passage of the dust cloud (Fig. 2). In Evora, the AOD increased from nearly 0.2 on 5 April to a about 0.8 on the next day. In Birkenes, the AOD raised from approximately 0.3 on 9 April to roughly 1.1 on 10 April (the AOD actually doubled in 10 April between the early morning and the late evening). The dominance of the dust in the AOD is evidenced by the strong decrease of AE to values below 0.6.

The 24 h forecasts produced by MetUM, ECMWF/MACC and NMMB/BSC-Dust overestimate the AOD on the 5 April in Saada, and, except for ECMWF/MACC, they underestimate the peak on 6 April. While MetUM reproduces the peak on 6 April, NMMB/BSC-Dust predicts it 6 h earlier, BSC-DREAM8b and ECMWF/MACC reproduce it 3 h earlier. DREAM8-NMME reproduces the AERONET AOD on 5 April but underestimates it on the following day whereas ECMWF/MACC mostly overestimates the AOD on both days. At Evora, most models overestimate the AOD on 6 April with the exception of NMMB/BSC-Dust and DREAM8-NMME. On 7 April MetUM and ECMWF/MACC mostly overestimate the AOD, while the rest of the models tend to underestimate it. The AOD forecast differs significantly for lead-times of 48 and 72 h. For example, while the 24 h ECMWF/MACC forecast overestimates the AOD in Saada on 5 and 6 April, the 72 h forecast mostly underestimates it. Similarly, at Evora, the 24 h forecast of NMMB/BSC-Dust slightly underestimates the AOD on 6 April whereas the 72 h forecast markedly overestimates it during the same day. At Birkenes, all models underestimate the AOD on the 10 April regardless of the forecast lead-time, which reflects the models' difficulties to transport dust in high concentrations up north. ECMWF/MACC presents a large spread between the different forecast times. While it features the best performance for the 24 h forecast, the model skill markedly decreased for the 72 h forecast.

The maps of daily MODIS AOD (Figs. 3 and S01–S03 in the Supplement) illustrate the progression of the dust cloud in agreement with the AERONET observations

and 40° N. The latter layer is a consequence of the uplift forced by the Atlas mountains (Fig. S09 in the Supplement).

The models show a large diversity in the 24 h forecast of extinction coefficient profiles, in particular for the 5 April when the satellite passes over the western margins of the continent and the adjacent Atlantic Ocean. On this day all models simulate a shallow near-surface dust layer over the continent south of 25° N but fail to reproduce the observed northward extension, except the ECMWF model. It shows a dust layer around 1 km a.g.l. but underestimates the intensity. The aerosol layer above 2 km is not simulated by NMMB/BSC-Dust, but visible, with an underestimated depth and height, in the other models. MetUM and ECMWF/MACC limit the vertical extent of the layer to 4 km and show the largest signal centred at 2 km as opposed to 3 km in the observations. Similarly, BSC-DREAM8b and DREAM8-NMME simulate this layer but with even smaller magnitudes.

On the 7 April the models mostly agree on the vertical distribution of the aerosol layer. Except for BSC-DREAM8b, all models represent the aerosol layer mostly confined within the first 2 km up to 40° N and the depth of the uplift north of 40° N is underestimated. BSC-DREAM8b, however, reproduces the depth of the observed layer extending up to 40° N but the depth of the uplift is overestimated and extended to 6 km. Finally, NMMB/BSC-Dust, BSC-DREAM8b and DREAM8-NMME underestimate the observed magnitude of the extinction coefficient, ECMWF/MACC overestimates it, and MetUM simulates values more in agreement with the observations.

4.4 Inter-comparison of synoptic conditions

The synoptic conditions are important for the origin and evolution of the dust cloud. We investigate the model performance to predict the synoptic conditions at mid-day compared to the Modern-Era Retrospective Analysis for Research and Application (MERRA) from NASA (Rienecker et al., 2011). This dataset is chosen as an independent reference that is not used by any of the models under investigation. Our analysis focuses on the day of dust emission (5 April), transport towards the Atlantic (7 April)

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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.

The Supplement related to this article is available online at doi:10.5194/acpd-15-26661-2015-supplement.

Acknowledgements. The authors acknowledge AERONET (<http://aeronet.gsfc.nasa.gov>) and thank the PIs of the AERONET stations used in this paper for maintaining the observation program, and the AERONET-Europe TNA (EU-ACTRIS grant no. 262 254) for contributing to calibration efforts. We also acknowledge the MERRA, CALIPSO and MODIS mission scientists and associated NASA personnel for the production of the data used in this research effort. MODIS data used in this paper were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC. S. Basart acknowledge the Catalan Government (BE-DGR-2012) as well as the CICYT project (CGL2010-19 652 and CGL2013-46 736) and Severo Ochoa (SEV-2011-00 067) programme of the Spanish Government. The NMMB/BSC-Dust and BSC-DREAM8b simulations were performed on the MareNostrum supercomputer hosted by BSC. Stephanie Fiedler acknowledges the funding of the European Research Council through the starting grant of Peter Knippertz (Number 257 543). Nicolas Huneeus acknowledges FONDAP 15 110 009. The database on dust concentrations at ground level was produced in the framework of the Grant Agreement LIFE10 ENV/IT/327 from the LIFE Programme of the European Commission. J. Pey has been partially funded by a Ramon y Cajal Grant (RYC-2013-14 159) from the Spanish Ministry of Economy and Competitiveness. Carlos Pérez García-Pando acknowledges the Department of Energy (DE-SC0 006 713), and the NASA Modeling, Analysis and Prediction Program.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



References

- Alpert, P., Krichak, S. O., Tsidulko, M., Shafir, H., and Joseph, J. H.: A dust prediction system with TOMS initialization, *Mon. Weather Rev.*, 130, 2335–2345, doi:10.1175/1520-0493(2002)130<2335:adpswt>2.0.co;2, 2002.
- 5 Aumont, O., Bopp, L., and Schulz, M.: What does temporal variability in aeolian dust deposition contribute to sea-surface iron and chlorophyll distributions?, *Geophys. Res. Lett.*, 35, L07607, doi:10.1029/2007GL031131, 2008.
- Bagnold, R. A.: *The Physics of Blown Sand and Desert Dunes*, Methuen, London, 1941.
- Balkanski, Y., Schulz, M., Claquin, T., and Guibert, S.: Reevaluation of Mineral aerosol radiative forcings suggests a better agreement with satellite and AERONET data, *Atmos. Chem. Phys.*, 7, 81–95, doi:10.5194/acp-7-81-2007, 2007.
- 10 Basart, S., Perez, C., Nickovic, S., Cuevas, E., and Baldasano, J. M.: Development and evaluation of the BSC-DREAM8b dust regional model over Northern Africa, the Mediterranean and the Middle East, *Tellus B*, 64, 18539, doi:10.3402/Tellusb.V64i0.18539, 2012.
- 15 Bauer, S. E. and Koch, D.: Impact of heterogeneous sulfate formation at mineral dust surfaces on aerosol loads and radiative forcing in the Goddard Institute for Space Studies general circulation model, *J. Geophys. Res.-Atmos.*, 110, D17202, doi:10.1029/2005JD005870, 2005.
- Benedetti, A., Reid, J. S., and Colarco, P. R.: International cooperative for aerosol prediction workshop on aerosol forecast verification, *B. Am. Meteorol. Soc.*, 92, ES48–ES53, doi:10.1175/bams-d-11-00105.1, 2011.
- 20 Benedetti, A., Baldasano, J. M., Basart, S., Benincasa, F., Boucher, O., Brooks, M., Chen, J.-P., Colarco, P. R., Gong, S., Huneus, N., Jones, L., Lu, S., Menut, L., Morcrette, J.-J., Mulcahy, J., Nickovic, S., Pérez, C., Reid, J. S., Sekiyama, T. T., Tanaka, T. Y., Terradellas, E., Westphal, D. L., Zhang, X.-Y., and Zhou, C.-H.: Numerical prediction of dust, in: *Mineral Dust – a Key Player in the Earth System*, edited by: Knippertz, P. and Stuut, J.-B., Springer, Dordrecht, 230–240, 2014.
- 25 Cuevas, E., Camino, C., Benedetti, A., Basart, S., Terradellas, E., Baldasano, J. M., Morcrette, J. J., Marticorena, B., Goloub, P., Mortier, A., Berjón, A., Hernández, Y., Gil-Ojeda, M., and Schulz, M.: The MACC-II 2007–2008 reanalysis: atmospheric dust evaluation and characterization over northern Africa and the Middle East, *Atmos. Chem. Phys.*, 15, 3991–4024, doi:10.5194/acp-15-3991-2015, 2015.
- 30

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Hsu, N. C., Tsay, S. C., King, M. D., and Herman, J. R.: Deep Blue retrievals of Asian aerosol properties during ACE-Asia, *IEEE T. Geosci. Remote*, 44, 3180–3195, doi:10.1109/TGRS.2006.879540, 2006.
- 5 Huneus, N., Schulz, M., Balkanski, Y., Griesfeller, J., Prospero, J., Kinne, S., Bauer, S., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Fillmore, D., Ghan, S., Ginoux, P., Grini, A., Horowitz, L., Koch, D., Krol, M. C., Landing, W., Liu, X., Mahowald, N., Miller, R., Morcrette, J.-J., Myhre, G., Penner, J., Perlwitz, J., Stier, P., Takemura, T., and Zender, C. S.: Global dust model intercomparison in AeroCom phase I, *Atmos. Chem. Phys.*, 11, 7781–7816, doi:10.5194/acp-11-7781-2011, 2011.
- 10 Huneus, N., Boucher, O., and Chevallier, F.: Atmospheric inversion of SO₂ and primary aerosol emissions for the year 2010, *Atmos. Chem. Phys.*, 13, 6555–6573, doi:10.5194/acp-13-6555-2013, 2013.
- Iversen, J. D. and White, B. R.: Saltation threshold on Earth, Mars and Venus, *Sedimentology*, 29, 111–119, 1982.
- 15 Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., laRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., and Torres, R.: Global iron connections between desert dust, ocean biogeochemistry, and climate, *Science*, 308, 67–71, 2005.
- Jiménez, E., Linares, C., Martínez, D., and Díaz, J.: Role of Saharan dust in the relationship between particulate matter and short-term daily mortality among the elderly in Madrid (Spain), *Sci. Total Environ.*, 408, 5729–5736, doi:10.1016/j.scitotenv.2010.08.049, 2010.
- 20 Kalenderski, S., Stenichikov, G., and Zhao, C.: Modeling a typical winter-time dust event over the Arabian Peninsula and the Red Sea, *Atmos. Chem. Phys.*, 13, 1999–2014, doi:10.5194/acp-13-1999-2013, 2013.
- 25 Karanasiou, A., Moreno, N., Moreno, T., Viana, M., de Leeuw, F., and Querol, X.: Health effects from Sahara dust episodes in Europe: literature review and research gaps, *Environ. Int.*, 47, 107–114, doi:10.1016/j.envint.2012.06.012, 2012.
- Kim, K. W., Kim, Y. J., and Oh, S. J.: Visibility impairment during Yellow Sand periods in the urban atmosphere of Kwangju, Korea, *Atmos. Environ.*, 35, 5157–5167, 2001.
- 30 Mahowald, N. M., Engelstaedter, S., Luo, C., Sealy, A., Artaxo, P., Benitez-Nelson, C., Bonnet, S., Chen, Y., Chuang, P. Y., Cohen, D. D., Dulac, F., Herut, B., Johansen, A. M., Kubilay, N., Losno, R., Maenhaut, W., Paytan, A., Prospero, J. A., Shank, L. M., and Siefert, R. L.:

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Shao, Y., Raupach, M. R., and Findlater, P. A.: Effect of saltation bombardment on the entrainment of dust by wind, *J. Geophys. Res.*, 98, 12719–12726, doi:10.1029/93JD00396, 1993.
- Shao, Y., Yang, Y., Wang, J., Song, Z., Leslie, L. M., Dong, C., Zhang, Z., Lin, Z., Kanai, Y., Yabuki, S., and Chun, Y.: Northeast Asian dust storms: real-time numerical prediction and validation, *J. Geophys. Res.-Atmos.*, 108, 4691, doi:10.1029/2003JD003667, 2003.
- Sokolik, I. N., Winker, D. M., Bergametti, G., Gillette, D. A., Carmichael, G., Kaufman, Y. J., Gomes, L., Schuetz, L., and Penner, J. E.: Introduction to special section: outstanding problems in quantifying the radiative impacts of mineral dust, *J. Geophys. Res.-Atmos.*, 106, 18015–18027, 2001.
- Tegen, I.: Modeling the mineral dust aerosol cycle in the climate system, *Quaternary Sci. Rev.*, 22, 1821–1834, 2003.
- Terradellas, E., Baldasano, J. M., Cuevas, E., Basart, S., Huneus, N., Camino, C., Dundar, C., and Benincasa, F.: Evaluation of atmospheric dust prediction models using ground-based observations, in: EGU General Assembly Conference, 7–12 April 2013, Vienna, Austria, Abstracts, Vol. 15, p. 8274, 2013.
- Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., Berntsen, T., Berglen, T., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Feichter, H., Fillmore, D., Ghan, S., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Horowitz, L., Huang, P., Isaksen, I., Iversen, I., Kloster, S., Koch, D., Kirkevåg, A., Kristjansson, J. E., Krol, M., Lauer, A., Lamarque, J. F., Liu, X., Montanaro, V., Myhre, G., Penner, J., Pitari, G., Reddy, S., Seland, Ø., Stier, P., Takemura, T., and Tie, X.: Analysis and quantification of the diversities of aerosol life cycles within AeroCom, *Atmos. Chem. Phys.*, 6, 1777–1813, doi:10.5194/acp-6-1777-2006, 2006.
- Vogel, B., Vogel, H., Bäumer, D., Bangert, M., Lundgren, K., Rinke, R., and Stanelle, T.: The comprehensive model system COSMO-ART – Radiative impact of aerosol on the state of the atmosphere on the regional scale, *Atmos. Chem. Phys.*, 9, 8661–8680, doi:10.5194/acp-9-8661-2009, 2009.
- Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H., and Young, S. A.: Overview of the CALIPSO Mission and CALIOP data processing algorithms, *J. Atmos. Ocean. Tech.*, 26, 2310–2323, doi:10.1175/2009jtech.1281.1, 2009.
- Woodward, S.: Modeling the atmospheric life cycle and radiative impact of mineral dust in the Hadley Centre climate model, *J. Geophys. Res.-Atmos.*, 106, 18155–18166, doi:10.1029/2000JD900795, 2001.

Woodward, S.: Mineral dust in HadGEM2, Hadley Centre Technical, Note 87, Met Office Hadley Centre, Exeter, Devon, UK, 2011.

Zhou, C. H., Gong, S. L., Zhang, X. Y., Wang, Y. Q., Niu, T., Liu, H. L., Zhao, T. L., Yang, Y. Q., and Hou, Q.: Development and evaluation of an operational SDS forecasting system for East

5 Asia: CUACE/Dust, Atmos. Chem. Phys., 8, 787–798, doi:10.5194/acp-8-787-2008, 2008.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

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

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneeus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

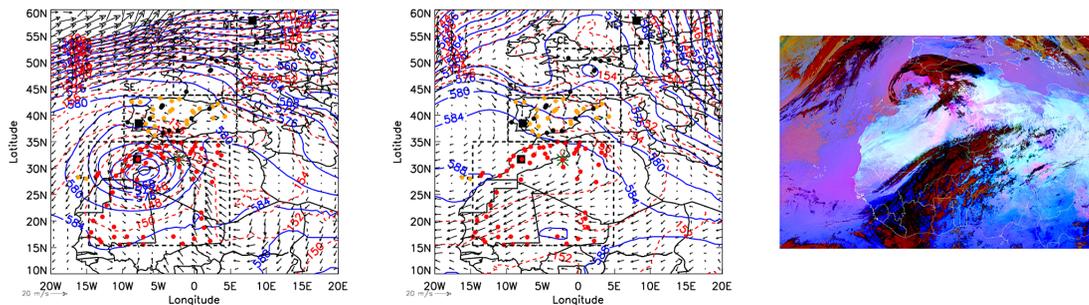


Figure 1. Geopotential height at 500 hPa (blue lines) and 850 hPa (red lines) for 5 and 10 April 2011 and wind field at 850 hPa. AERONET (orange), surface concentration (black), surface wind (green) and radiosounding (brown) stations used in this study are presented. Southern, Central and Northern Europe (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.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

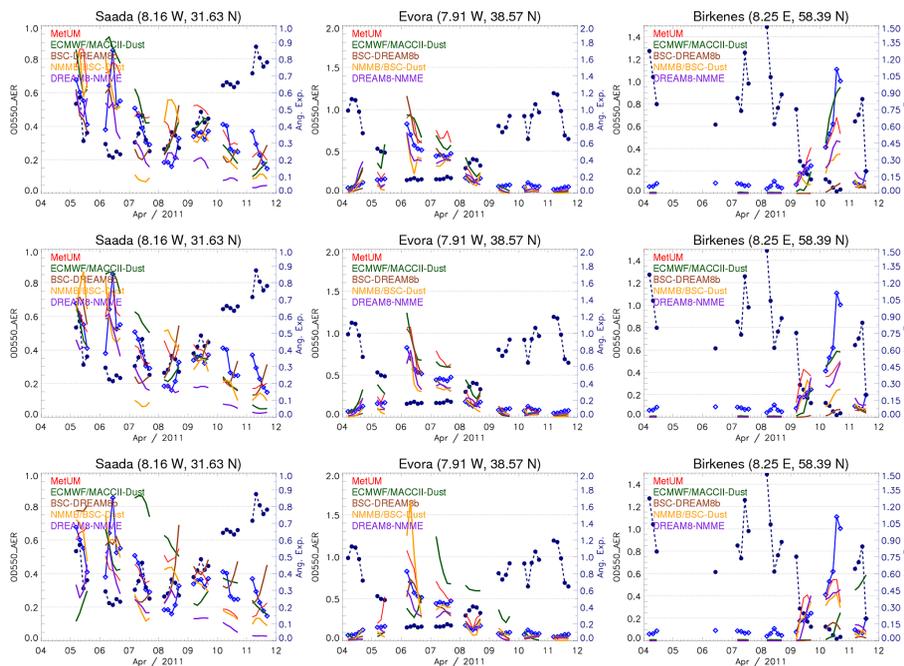


Figure 2. Total AOD at 550 nm at three selected sites from the AERONET network (blue line) and 24 (first row), 48 (middle row) and 72 h (bottom row) forecast of the model MetUM (red), ECMWF/MACC (green), BSC-DREAM8b (brown), NMMB/BSC-Dust (orange) and DREAM8-NMME (purple) are illustrated. The Angström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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

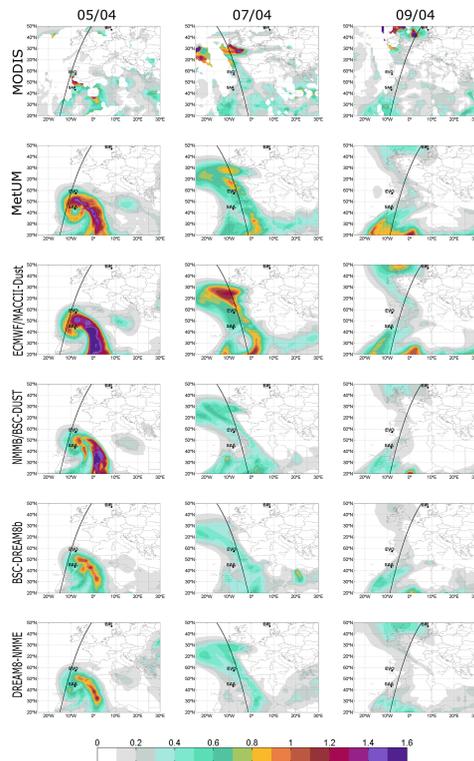


Figure 3. Maps of daily total AOD at 550 nm from MODIS (first row) and corresponding 24 h forecast of models MetUM (second row), ECMWF/MACC (third row), NMMB/BSC-DUST (fourth row), BSC-DREAM8b (fifth row) and DREAM8-NMME (sixth row) for 5 (first column), 7 (second column) and 9 (third column) April 2011. 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.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

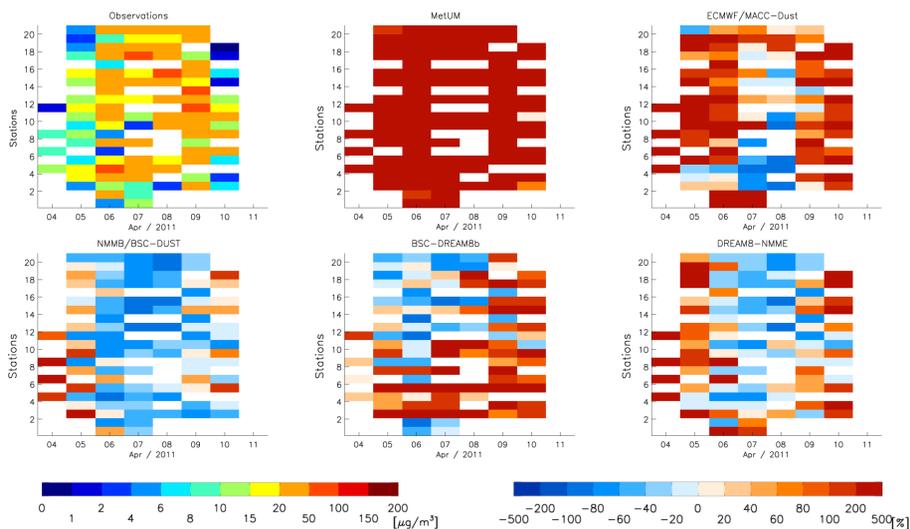


Figure 4. Daily measured surface concentration $[\mu\text{g m}^{-3}]$ and normalized bias of corresponding 24 h forecast surface concentration [%] at stations illustrated in Fig. 1. Each row corresponds to one of the stations. Stations are ordered from south to north and white colour corresponds to days 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.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

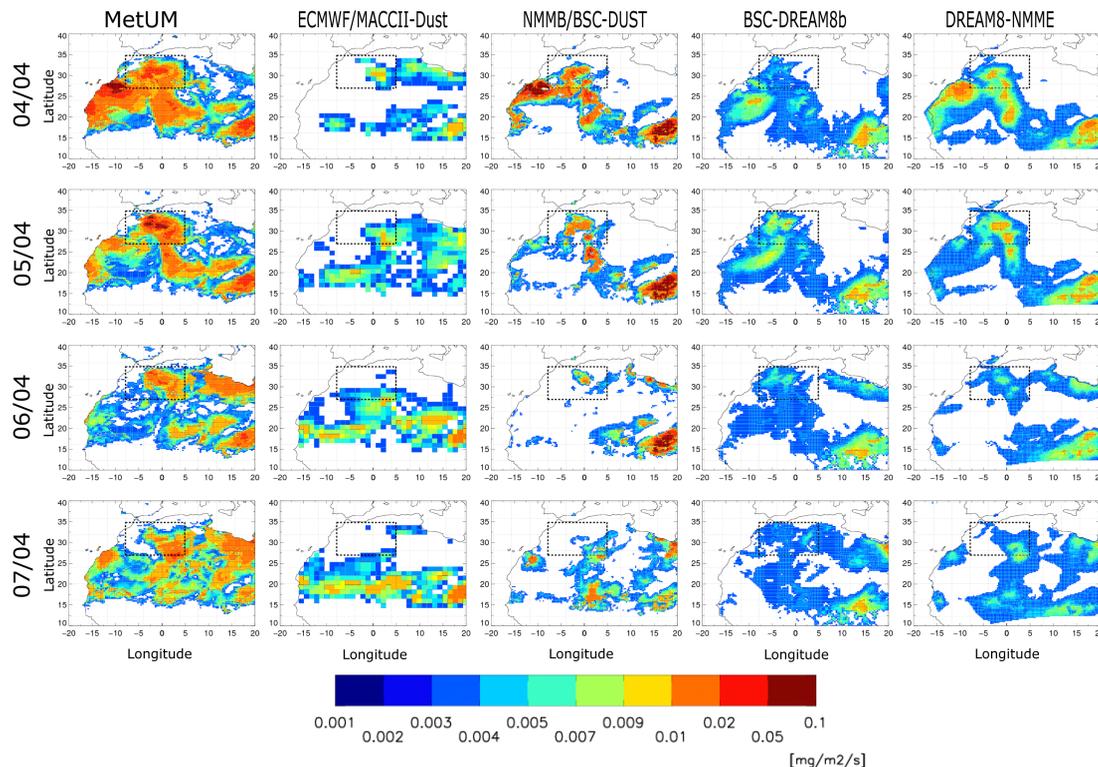


Figure 5. Forecasted daily average emission with 24 h lead-time for the models MetUM (first column), ECMWF/MACC (second column), NMMB/BSC-DUST (third row), BSC-DREAM8b (forth column) and DREAM8-NMME (fifth row). Dashed box illustrates region used in the time series emissions illustrated in Fig. 6.

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

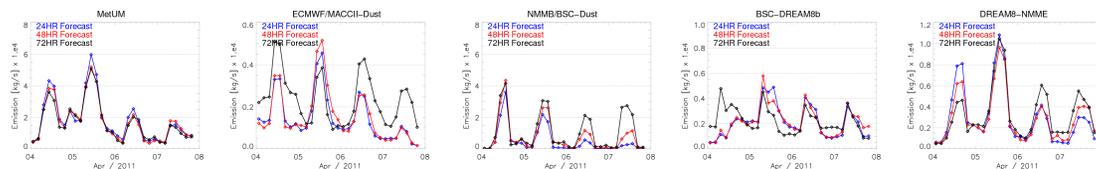


Figure 6. Time series of 3 hourly emissions from models MetUMTM, ECMWF/MACC, NMMB/BSC-Dust, BSC-DREAM8b and DREAM8-NMME with 24, 48 and 72 h lead-time (blue, red and black respectively).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

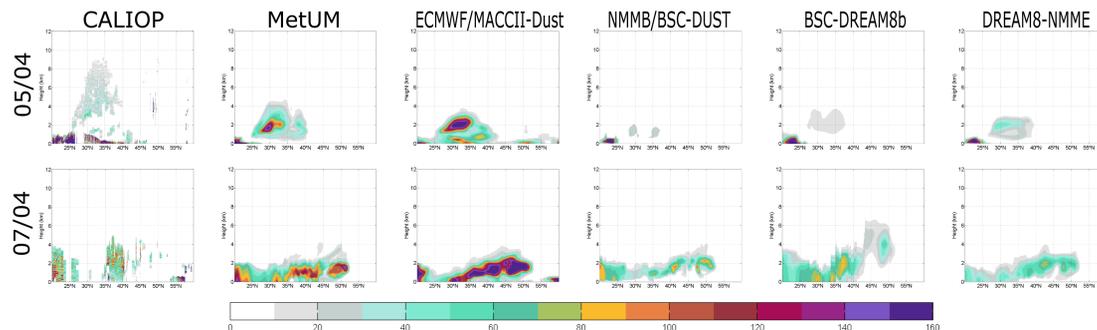


Figure 7. Profiles of measured total extinction coefficient at 532 nm from the CALIOP instrument onboard of the CALIPSO satellite and 24 h forecasted dust extinction coefficient profiles at 532 nm from models MetUM, ECMWF/MACC, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME. Conditions are presented for 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.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

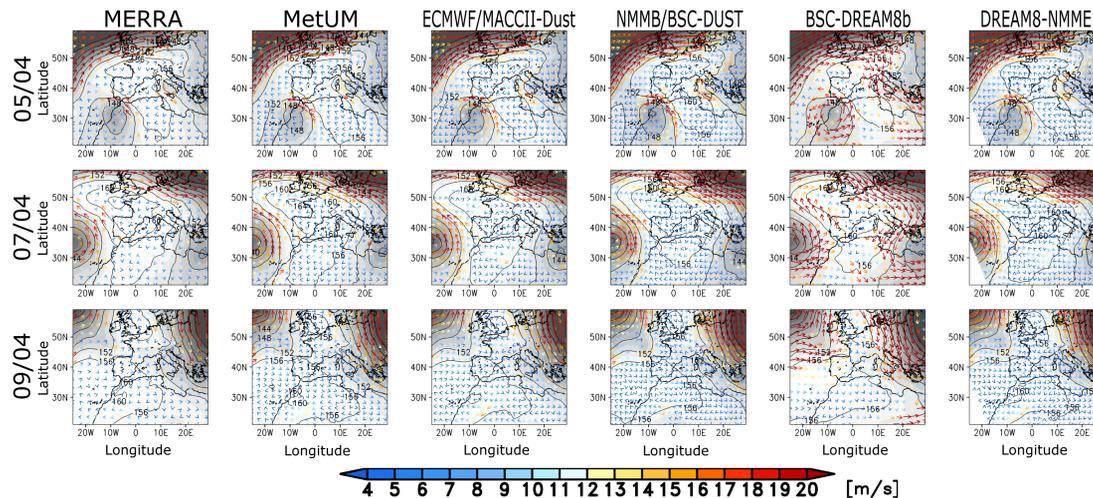


Figure 8. The geopotential height (contours) and wind speed stream lines at 850 hPa on 5 (first row), 7 (second row) and 9 (third row) April 2011 at 12:00 UTC from MERRA reanalysis and the 24 h forecast from MetUM, ECMWF/MACC, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME (from left to right).

Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

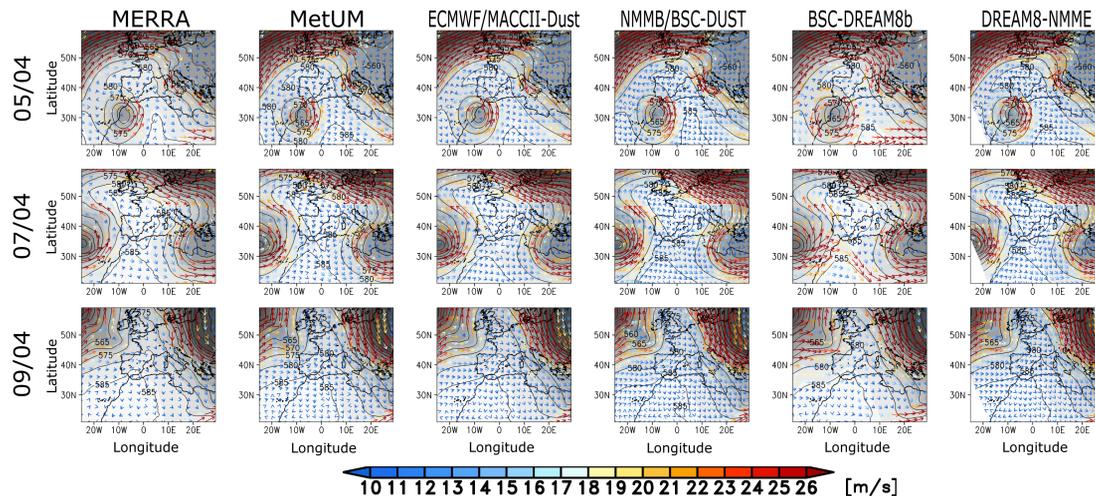


Figure 9. Same as Fig. 8 but for 500 hPa.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

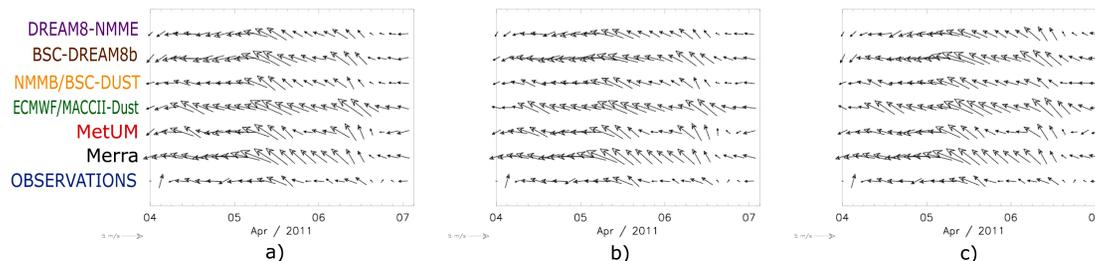


Figure 10. Time series of near-surface wind speeds in dust source region. Three-hourly values of the 10 m-wind speed from observations and re-analysis (MERRA), global models and regional models for the period 4 April 2011 to 7 April 2011 with **(a)** 24 h lead time, **(b)** 48 h, and **(c)** 72 h. Observations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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

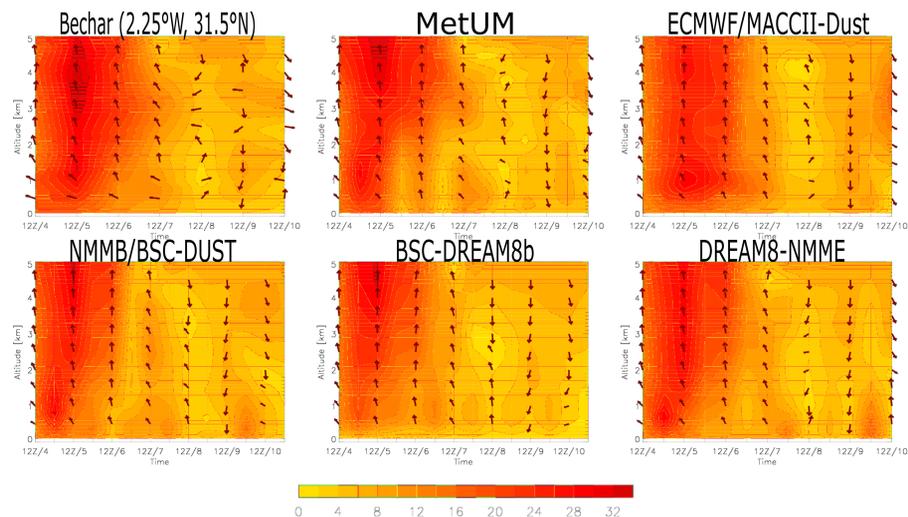


Figure 11. Profiles of measured wind speed (m s^{-1} , filled contours) and direction (vectors, first column) between the 4 and 10 April from radiosounding at Bachar (2.25°W , 31.5°N ; first row) and the corresponding 24 h forecast of models MetUM, ECMWF/MACC, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forecasting the North African dust outbreak towards Europe in April 2011

N. Huneus et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

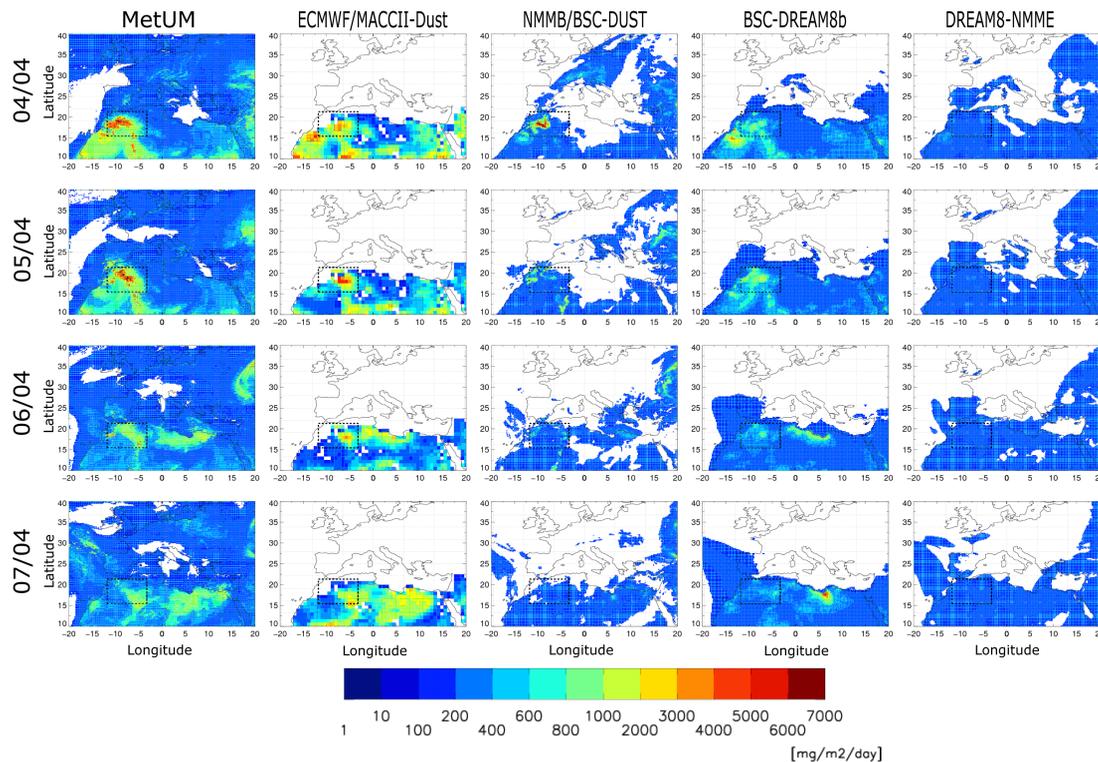


Figure 12. Total accumulated forecasted daily deposition with 24 h lead time for the models MetUM, ECMWF/MACCII-Dust, NMMB/BSC-DUST, BSC-DREAM8b and DREAM8-NMME (from left to right).