



Dust model
comparison
methodology

I. Biniotoglou et al.

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A methodology for investigating dust model performance using synergistic EARLINET/AERONET dust concentration retrievals

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Dust model
comparison
methodology**

I. Biniotoglou et al.

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

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Abstract

Systematic measurements of dust concentration profiles at continental scale were recently made possible by the development of synergistic retrieval algorithms using combined lidar and sun photometer data and the establishment of robust remote-sensing networks in the framework of Aerosols, Clouds, and Trace gases Research Infrastructure Network (ACTRIS)/European Aerosol Research Lidar Network (EARLINET). We present a methodology for using these capabilities as a tool for examining the performance of dust transport models. The methodology includes considerations for the selection of a suitable dataset and appropriate metrics for the exploration of the results. The approach is demonstrated for four regional dust transport models (BSC-DREAM8b v2, NMMB/BSC-DUST, DREAMABOL, DREAM8-NMME-MACC) using dust observations performed at 10 ACTRIS/EARLINET stations. The observations, which include coincident multi-wavelength lidar and sun photometer measurements, were processed with the Lidar-Radiometer Inversion Code (LIRIC) to retrieve aerosol concentration profiles. The methodology proposed here shows advantages when compared to traditional evaluation techniques that utilize separately the available measurements such as separating the contribution of dust from other aerosol types on the lidar profiles and avoiding model assumptions related to the conversion of concentration fields to aerosol extinction values. When compared to LIRIC retrievals, the simulated dust vertical structures were found to be in good agreement for all models with correlation values between 0.5 and 0.7 in the 1 to 6 km range, where most of dust is typically observed. The absolute dust concentration was typically underestimated with mean bias values of -40 to $-20 \mu\text{g m}^{-3}$ at 2 km, the altitude of maximum mean concentration. The reported differences among the models found in this comparison indicate the benefit of the systematic use of the proposed approach in future dust model evaluation studies.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Desert dust is emitted from arid regions around the world, and in many cases it is the dominant aerosol type. Dust aerosols affect the radiation balance and temperature structure of the atmosphere by interacting both with short- and long-wave radiation (Sokolik and Toon, 1996; Pérez et al., 2006b; Balkanski et al., 2007); they also affect cloud micro-physical properties and precipitation patterns by acting as cloud condensation and ice nuclei (DeMott et al., 2003; Karydis et al., 2011) and, due to their large spatial and temporal extent, have an important effect on climate (Rosenfeld et al., 2001). The main source regions of dust are located in Northern Africa and Western and Central Asia but due to the prevalent wind patterns they have significant impact on the air quality of Europe, North America, and East Asia, far away from their sources, affecting the health of large populations (Morman and Plumlee, 2014). Additionally, mineral dust aerosols are suspected to be an important source of soluble iron in the marine ecosystems and, thus, an important factor of marine bioproduction (Mahowald et al., 2010; Nickovic et al., 2013; Gallisai et al., 2014).

Given this complexity, dust models are an important tool for studying the complete dust cycle in the atmosphere. Such models simulate dust's life-cycle including production in arid regions, transport in the atmosphere, and wet and dry deposition (Tegen, 2003). These models, which can produce complete 3-D fields of dust concentration, can be used to provide operational dust forecasts and, in total, give a bird's-eye view of dust in the atmosphere. Dust models have been used, for example, to quantify the effect of dust on air quality of Mediterranean cities (Jiménez-Guerrero et al., 2008), to study the effects of dust on weather forecasts (Pérez et al., 2006b), and to quantify the impact of lofted dust particles on cloud formation (Klein et al., 2010; Solomos et al., 2011). To perform these simulations, models rely on the physical description of atmospheric processes, on the choice of parameterization, and on the tuning of individual components in the model; consequently, modeling outputs need to be monitored against in situ and remote sensing measurements to evaluate their performance. When

AMTD

8, 3605–3666, 2015

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



used as a forecasting tool, models can assimilate remote sensing measurements to improve their forecasting skill (Benedetti et al., 2009; Sekiyama et al., 2010; Wang et al., 2014).

Most dust model evaluation methods are based on measurements of columnar aerosol properties. A typical quantity used is, for example, aerosol optical depth (AOD) measured by the Aerosol Robotic Network (AERONET) photometer network or satellite platforms such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (e.g Pérez et al., 2011; Basart et al., 2012b). In these comparisons, the modeled dust volume concentration is converted to dust optical depth using spherical particle approximation and a modeled size distribution. These evaluation attempts are limited by the contribution of non-dust aerosols and so are restricted to cases or regions where dust is the dominant aerosol type (e.g. Basart et al., 2009; Cuevas et al., 2014).

While the columnar properties of dust are systematically studied, the vertical distribution of dust is a property that has not been explored to the same extent, even though this could have a significant effect in the total model performance. A better vertical distribution, for example, could improve the transport and removal component of the dust model and would have significant impact on the quality of the air-quality forecasts and the study of dust-radiation and dust-cloud interactions (e.g. Wang et al., 2014).

The vertical distribution of dust has been previously studied using lidar optical property profiles, but these studies have focused on few case studies (e.g. Pérez et al., 2006a; Uno et al., 2006; Müller et al., 2009; Heinold et al., 2009). Other studies have compared model optical profiles with lidar long-term observations but are limited, however, to single locations. For example, Mona et al. (2014) have presented a systematic examination of BSC-DREAM8b model dust concentration vertical distribution over Potenza, Italy, for the 2000–2012 period, using lidar-derived backscatter and extinction profiles. Similarly, Gobbi et al. (2013) compared the lidar dust extinction profiles with those modeled by BSC-DREAM8b over Rome, Italy during the 2001–2004 period. Results from both studies indicate that the dust model represented adequately the vertical distribution of dust despite underestimating the total extinction profiles.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Dust model
comparison
methodology**

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In this paper, we examine a strategy for cross-examining dust model vertical distribution and volume concentration profiles retrieved using lidar/sun-photometer synergy, at a continental scale. The development of advanced algorithms allows the retrieval of dust concentration profiles using the synergy of lidar and sun/sky photometer data (e.g. Chaikovsky et al., 2015; Ansmann et al., 2012; Lopatin et al., 2013) and these can be directly compared to the simulated dust distribution. Under certain assumptions, these algorithms can separate the contribution of dust from that of other aerosol types and so can be used for examining the dust model performances even in mixed aerosol cases. The retrieved dust concentration products include information about the actual aerosol size distribution – instead of relying on the model simulated size distribution – further improving the results. Up to now, the comparison of these algorithms with models has been restricted to single cases; for example, Tsekeri et al. (2013) presented a case study where the output of BSC-DREAM8b model was compared with dust concentration retrieved using the Lidar/Radiometer Inversion Code algorithm (LIRIC) over Athens, Greece, finding satisfactory agreement.

The recent implementation of LIRIC in many advanced EARLINET remote sensing stations (Chaikovsky et al., 2012) allows the systematic examination of model performance in a wider geographical region. In this paper we present a general methodology for the comparison of measured and modeled vertical dust distribution, including the strategies that could be used, the caveats that should be taken care of, and suggest the appropriate metrics that could help explore the dataset. Next, we apply this methodology to compare dust concentration profiles retrieved at 10 European remote sensing sites to 4 European regional dust transport models.

The four models that participate in this inter-comparison are BSC-DREAM8b v2, NMMB/BSC-Dust, DREAMABOL, and DREAM8-NMME-MACC. All four models contribute to the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) that was established by the World Meteorological Organization (<http://www.wmo.int/sdswas>). The SDS-WAS aims to improve the present capabilities for reliable sand and dust storm forecasts; to do this it supports the development of comprehensive, co-

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ordinated and sustained observations and modeling capabilities of these events. The SDS-WAS consists of two Regional Nodes, one for Northern Africa, Middle East and Europe (NA-ME-E) – set in Spain – and one in Asia – set in China; each of these nodes deals with both operational and scientific aspects related to atmospheric dust monitoring and forecasting. All the models participating in the present study contribute to the NA-ME-E Regional Node.

The rest of the paper is structured as follows: in Sect. 2 we present the EARLINET and AERONET remote sensing networks, we provide an overview of the new retrieval algorithms, such as LIRIC, and present the 4 dust models used in this study. In Sect. 3 we introduce the methodology of the cross-examination, and present the appropriate statistical indicators that can be used for future evaluation of dust models. Finally, in Sect. 4 we present the results obtained by applying this methodology to real measurements. In Sect. 5 we give conclusions and indicate directions for future work.

2 Algorithms and Models

2.1 Measurement networks

The systematic observation of the vertical distribution of dust on continental scale is possible due to the development of regional lidar remote sensing networks in main dust outflow regions like the European Aerosol Research Lidar Network (EARLINET, Pappalardo et al., 2014), the AD-Net in East Asia (Sugimoto et al., 2005), the Latin American Lidar Network (LALINET) in Latin America (Barbosa et al., 2014; Guerrero-Rascado et al., 2014), and the global Micropulse Lidar Network (MPLNET, Campbell et al., 2002). This study focuses on EARLINET, a lidar network that has been established in 2000 with the aim to provide comprehensive information for the aerosol vertical distribution over Europe (Bösenberg et al., 2001). Currently, 27 stations participate actively in the network with regular contribution of data. The network includes 17 stations with multi-wavelength Raman systems, while 18 stations perform depolarization

**Dust model
comparison
methodology**

I. Biniotoglou et al.

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

measurements, giving important information on the shape of the measured particles. All stations in the network perform climatological measurements – three times a week according to a predefined measurement schedule – together with extra measurements in special events, dust measurements based on an alerting system, and intensive observational measurement campaigns (Pappalardo et al., 2014). Considerable attention has been given within EARLINET to improve and homogenize the performance of the systems, including hardware test, algorithm test on synthetic data, and system intercomparison campaigns (Matthias et al., 2004; Böckmann et al., 2004; Pappalardo et al., 2004). The optical products calculated from all the systems are stored in a standardized data format in a central database and are available for external users. The first volumes of the EARLINET database have been published in biannual volumes at the World Data Center for Climate (The EARLINET publishing group 2000–2010 et al., 2014).

Similarly, regional-to-global sun/sky photometer networks like Aerosol Robotic Network (AERONET, Holben et al., 1998), Global Atmosphere Watch – Precision Filter Radiometer network (GAW-PFR, McArthur et al., 2003), and Skyrad Network (SKYNET, Takamura and Nakajima, 2004; Kim et al., 2008) have also been developed. Many of these instruments are collocated with lidar system of the corresponding lidar networks, thus allowing the development of synergistic algorithms. In this study we use AERONET, a global network of automatic sun/sky-scanning photometers that was created in the mid 90's in order to provide global aerosol data not provided at the time by satellites and to act as a validation platform for future satellite missions. Its current aim is to provide long-term, continuous measurements of aerosol optical and microphysical properties. The network consists of standardized photometers produced by Cimel Electronique and all participating instruments undergo regular calibration and intercomparison with reference instruments. The photometers in the AERONET network perform both direct-sun and sky-scanning almucantar measurements at several wavelengths (between 340 and 1640 nm). The output of direct-sun measurements is the AOD in several wavelengths, while the sky-scanning measurements are also use

for retrieving aerosol microphysical properties (Dubovik and King, 2000; Dubovik et al., 2006). The processing is centrally performed and the results are made public in near-real time.

2.2 Retrieval algorithms

5 Different levels of lidar-based remote sensing products can be used for the evaluation of dust models, ranging from uncalibrated range-corrected signals (RCS) to dust mass concentration profiles retrieved through synergistic algorithms (Mona et al., 2012); an overview of the available lidar products is given in Table 1. The first level of products that can be used for model evaluation are range-corrected lidar signals that give qualitative information about the aerosol structure in the atmosphere (Kovalev and Eichinger, 2004); they provide an overview of dust transport processes and help check the geometrical properties of the simulated dust layers. Being almost raw lidar products, RCS can be provided even by simple lidar systems and some ceilometers (Wiegner et al., 2014; Madonna et al., 2014).

15 On a second level, retrieved optical properties, i.e. profiles of aerosol backscatter and extinction coefficients, give quantitative information about the total aerosol content (Klett, 1981, 1985; Ansmann et al., 1992) with well characterized uncertainties (e.g. Rocadenbosch et al., 2012); these products can be used to study both geometrical and intensive properties of the dust layers and are especially useful for optically thick lofted dust layers (e.g. Papayannis et al., 2005). They can not be used reliably, however, in cases of dust mixtures, as they do not separate the contribution of dust from other atmospheric aerosols, like smoke and pollution. In most cases no comparison can be made in the Planetary Boundary Layer (PBL) where the load of fine anthropogenic aerosols is always expected to be high, especially in most measurement sites in Europe.

25 If depolarization measurements are available, this problem is partly solved by a third level of analysis, which retrieves the dust backscatter coefficient profiles, based on known depolarization ratios of dust and other aerosol types (Shimizu et al., 2004;

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



for the missing parameter. For example, the POLIPHON algorithm (Ansmann et al., 2011, 2012) is based on dust depolarization and extinction-to-backscatter coefficient ratio (aerosol lidar ratio) observed during the SAMUM campaign and long-term EARLINET measurements of dust transport events over Europe. In addition, POLIPHON
5 uses the volume-to-AOD ratio derived from the photometer to approximate the variable volume-to-extinction ratio for dust and smoke aerosols. Extending this approach, Mamouri and Ansmann (2014) use laboratory measurements of fine and coarse dust depolarization ratio to further separate these two sub-classes of dust. In contrast, Nemuc et al. (2013) use properties from the Optical Properties of Aerosols and Clouds (OPAC) database (Hess et al., 1998) as a basis for their separation of dust and non-
10 dust properties. Other approaches combining lidar measurements with airborne measurements or complex AERONET processing have also been developed (Cuesta et al., 2008; Lewandowski et al., 2010).

The second category of algorithms pursues a more tight integration of lidar and photometer data. Specifically, the retrieved volume concentration profiles are calculated by optimally fitting the aerosol concentration to the lidar and photometer measurements (Dubovik, 2005). In the case of GARRLiC (Lopatin et al., 2013), the optimal fit of the lidar and photometer measurements is found using a multi-term least square approach. Similarly, LIRIC (Chaikovsky et al., 2015) uses the AERONET inversion products to de-
15 rive the intensive properties of fine and coarse aerosols; consequently, the algorithm finds the optimal profiles of these types based on lidar measurements and total-column volume concentration profiles provided by AERONET.

In this paper, we use results from the LIRIC algorithm to show the benefit of using such algorithms for dust model evaluation. LIRIC was chosen as it takes full advantage of the remote sensing networks EARLINET and AERONET, and is used by a large
25 number of aerosol remote sensing stations in Europe (Chaikovsky et al., 2012); the results we present are, nevertheless, applicable to similar datasets retrieved by other algorithms. The details of LIRIC can be found in Chaikovsky et al. (2015) so only a brief overview is given here.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The DREAM8-NMME-MACC is developed and operated at the South East European Virtual Climate Change Center (SEEVCCC; <http://www.seevccc.rs/>), Serbia. The DREAM8 model is embedded in the NCEP Nonhydrostatic Mesoscale Model (NMM) on E-grid (Janjic et al., 2001) while initial and boundary conditions are taken from ECMWF global forecast. This version of DREAM8 is assimilating ECMWF dust analysis in dust initial field, with dust sources defined from Ginoux et al. (2001). DREAM8-NMME-MACC provides daily dust forecasts available at the SEEVCCC website.

Finally, the NMMB/BSC-Dust model is a regional to global dust forecast system designed and developed at BSC in collaboration with NOAA NCEP, NASA Goddard Institute for Space Studies and the International Research Institute for Climate and Society (IRI) (Pérez et al., 2011). It is an online multi-scale atmospheric dust model fully embedded into the NMM on B-grid (Janjic et al., 2011). As with DREAM, this model assumes a viscous sublayer between the smooth desert surface and the lowest model layer while it includes a physically based dust emission scheme, which explicitly takes into account saltation and sandblasting processes (White, 1979; Marticorena and Bergametti, 1995; Marticorena et al., 1997). The NMMB/BSC-Dust model has been evaluated at regional and global scales (Pérez et al., 2011; Haustein et al., 2012). It provides operational dust forecast for the Barcelona Dust Forecast Center (BDFC; <http://dust.aemet.es/>) the first specialized center of the WMO for dust prediction.

While each model has a different setup, they use common description of dust size distribution using 8 size bins between 0.1 and 10 μm (Pérez et al., 2011) with intervals taken from Tegen and Lacis (1996) and Pérez et al. (2006a). Dust within each transport bin is assumed to have a time-invariant log-normal distribution (Zender et al., 2003) with the shape of the distribution fixed to a mass median diameter of 2.524 μm (Shettle, 1986) and a geometric SD of 2.0 (Schulz et al., 1998). The dust mass in each bin depends on model processes. Many other subcomponents are shared between some of the models.

In the present analysis, various model output fields at 3 hourly resolution are compared. The research teams at the modeling centers configured their model experiments

independently and not necessarily following the setup of their respectively daily operational forecast. The spatial resolution, domain size, initial and boundary conditions, differ, in addition to the different physical parameterizations implemented in the models summarized in Table 2.

3 Methodology

In this section we present the considerations for constructing the remote sensing dataset and choosing statistical indicators that can be used for the model and measurement cross-examination. Special attention is given in selecting a representative dataset, avoiding possible biases due to the geographical restrictions of the measurement location, the selection of vertical resolution, and the effect of local dust sources in the study of the PBL. The considerations that guided our choices are given below.

Remote sensing profiling measurements can be used to improve dust modeling efforts at three different levels: diagnostic evaluation, Near Real-Time (NRT) evaluation, and assimilation (Seigneur et al., 2000; Sicard et al., 2015; Wang et al., 2014). In the first case, remote sensing measurements are used to study the model performance during a past study period. The aim of such a study is to evaluate the model performance, understand its behavior and limitations, and suggest improvements either by tuning applied parameterizations or by changing the representation of processes in the models. The evaluation can focus on individual cases of dust transport events or follow a statistical approach, covering a larger time period.

In the case of NRT evaluation, the measured profiles are used to provide insight on the performance of an operational forecast. The aim of such an evaluation is to provide a quick overview of the model performance to the end users while it can also help modelers detect possible problems in time. The time requirements for the processing of such observations are moderately strict, as data could be useful even one day after the measurement time. In the case of assimilation, the remote sensing measurements are used by the model to improve the forecasted model concentrations. The time re-

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



quirements for assimilation depend on the assimilation system used but are typically of a few hours.

In this study we focus on the first case, that is, diagnostic evaluation of the model performance. We choose to study an extended time and space period that gives us better representation of different meteorological conditions, dust transport paths, and measurement locations. However, the considerations and metrics presented here can also be applied to the NRT evaluation scenario.

As shown in Sect. 2.2, synergistic retrieval algorithms can help avoiding possible comparison biases caused by the presence of aerosol mixtures, by separating the dust contribution from that of other aerosol types. However, direct comparison with dust models should be done carefully, because the part of aerosol identified as dust could differ depending on the selected algorithm. Thus, in the case of LIRIC dust is assumed to be a particle component larger than $\sim 0.5 \mu\text{m}$ in radius. On the other hand, the total dust load predicted by the models also includes smaller particle sizes in the first few bins of the dust size distribution. The contribution of these small particles in the total aerosol load should be typically low, especially near the source (d’Almeida, 1987), but could become more important in cases of long-range dust transport where the larger particles have been gravitationally removed (Mamouri and Ansmann, 2014). When using a statistical approach including different locations and transport paths, as in the present study, this effect is expected to be small. The exact amount of fine-mode transported dust is an open issue and should be further investigated. The fine mode contribution, however, is expected to be important when performing a case study evaluation and then only specific bins from the model output should be used instead.

In the case of statistical model evaluation, the selected measurement profiles should also be independent to give a correct representation of the model performance. Specifically, it should be avoided that the used measurements from each station sample the same event multiple times, but should instead measure independent dust transport events. This consideration is less important when using data from automatic instruments; in the case of EARLINET, however, the available dataset could contain data

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Dust model
comparison
methodology**

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



from long observations periods and intensive measurement campaigns, as described in Sect. 2.1. Ideally, only a climatological dataset would be used, but the number of the available cases would be limited from the measurement frequency, the sporadic nature of dust transport episodes, and, when using synergistic algorithms, the availability of AERONET data. In this study we consider to sample independent dust transport events by measurements that had at least 24 h time difference, compatible with the expected variability of tropospheric aerosols (Anderson et al., 2003a, b).

The vertical resolution of lidar and dust model profiles should be taken into account during their comparison. The lidar signals have a raw vertical resolution of a few meters and the final products have an effective resolution of a few hundred meters depending on filtering procedures and smoothness constraints used in the retrieval (Pappalardo et al., 2004). The vertical resolution of the models, on the other hand, is typically coarser but depends on the vertical resolution of the meteorological driver (Simmons and Burridge, 1981; Mesinger, 1984). When performing a statistical comparison, the different vertical resolutions are less important as the features of individual dust transport cases will be smoothed. When comparing aerosol extensive properties (both optical and concentrations) the remote sensing profiles should be upscaled to the model resolution. When, however, the aim of the comparison is to evaluate the dust layer geometrical properties and values at a specific location, e.g. the peak concentration values, the finer resolution remote sensing profiles should be used. In this study and in order to facilitate the comparison of models of different vertical resolutions, we interpolate all available profiles to a common 100 m vertical resolution. We used this resolution to examine the geometrical properties and peak concentration value of dust layers, but used 500 m averages to calculate the statistics on the vertical profiles presented in the next section. The models simulate the dust concentration profiles on a specified horizontal grid, so bilinear interpolation was used to estimate the concentration values at the exact location for each station. Linear interpolation was also utilized to estimate the concentration profiles at the exact time of the available measurements.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Correct representation of the dust mixing in the PBL can impact the forecasted air quality and also affect the removal processes of dust in the model. In this process, dust is mixed with locally produced aerosols, so lidar optical profiles cannot be used to directly study the dust effect. The mass retrieval algorithms, like LIRIC, are able to separate the dust component in the PBL and give some insights to study this process, even though several limitations remain. Firstly, local dust sources could contribute to the dust load in the PBL (Korcz et al., 2009) although the exact effect of such sources to the vertical dust distribution, to our knowledge, has not been systematically studied. Secondly, as dust comes in contact with other types of particles and high relative humidity, some of the assumptions of the retrieval algorithms could be invalid. For example, polluted and humid PBL can lead to dust being coated and water layer to form on the dust particles, changing their optical properties (Levin et al., 1996; Kumar et al., 2011b). Such effect could be important for the exact quantitative characterization of dust but does not completely prevent studying the mixing of dust in the PBL. Lastly, most lidar systems have a high overlap function and can only detect the initial mixing of dust in the upper parts of the PBL. Given these factors, the study of this mixing process could be done better for specific case studies. If a statistical approach is followed, the dataset should be large enough to give significant results, as only few profiles cannot capture this dynamical mixing phenomenon.

The direct output of all the synergistic retrieval algorithm mentioned before is volume concentration profiles of fixed aerosol types. This can be converted to mass concentration profiles, the typical output of dust transport models, by using the aerosol bulk density. In the case of dust, the typically used value is 2.6 g cm^{-3} (Köpke et al., 1997; Ansmann et al., 2012) while the actual bulk concentration could differ by location (e.g. Todd et al., 2007). In the case of dust model evaluation, however, selecting a value of 2.6 g cm^{-3} is compatible with the assumptions of most dust transport models (Tegen and Fung, 1994; Nickovic et al., 2001; Yumimoto et al., 2012), and thus a further reason for discrepancies is removed from this study.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



We perform the comparison firstly by examining single statistical indicators of each measurement case and secondly looking into indicators at different altitude ranges. This approach allows assessing both the total performance of the models and the detailed performance across the profile. The single parameters examined are total concentration, peak concentration value, and center of mass of the dust vertical distribution. For the profile parameters, apart from the average profiles, we examine the mean bias error, correlation coefficient, root mean square error, and fractional gross error. This set of parameters was chosen because it can provide a detailed view of performance while remaining compatible, as much as possible, with the metrics already in use in the SDS-WAS columnar evaluation.

An important indicator for model vertical profiles is the center of mass (CoM), a parameter that gives in a single number an indication of the altitude of the dust distribution. In cases where a single aerosol layer is present in the atmosphere, the CoM gives an indication of its mean altitude; in case of multiple layers, however, the CoM could be located in areas without any considerable dust load (Mona et al., 2006, 2014).

The second single-value measure to compare is the dust total concentration, calculated across the altitude range where both measured and model profiles provide valid results. In this way, this comparison will be a little different than comparing directly columnar measurements, as in the case of comparing photometer and total column model values. In the latter case the used range includes the lower few hundred meters of the profile, thus including the contribution of local dust sources to the total column aerosol load, possibly producing a bias in the measurements.

A third metric examined is the peak value of the profile, a value typically indicating the main vertical location of the dust plume. In cases where the main dust mass is located near the ground, the lidar system can fail to detect the true maximum, and instead show a maximum value at the lowest point of the profile, i.e. first point of full overlap. In these cases we considered as maximum value the first lofted layer peak, located as the first peak after the first local minimum of the concentration profile.

**Dust model
comparison
methodology**

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The profile statistical indicators were calculated by first averaging the compared profiles at 500 m resolution then computing a set of statistics for each altitude range. This resolution was chosen as a trade-off between detailed aerosol structure and the signal noise of the lidar measurements. This value, however, needs to be determined in each study based on the number of available profiles. Apart from the mean value profiles, the first set of metrics used are the mean bias, and the root mean square error (RMSE); being expressed in units of concentration, these values are suitable for the intercomparison of models but can be misleading for the performance of models with altitude. In addition, RMSE is strongly dominated by the largest values, due to the squaring operation, so in cases where prominent outliers occur, the usefulness of RMSE is questionable and the interpretation becomes more difficult. These limitations are addressed using a second set of statistical indicators, including correlation coefficient, fractional bias, and fractional gross error. Fractional bias is a normalized measure of the mean bias and indicates only systematic errors which lead to under/over-estimation of the measured values. Similarly, the fractional gross error is a positive-defined indicator that gives the same figure with respect to under- and over-estimation. Definitions of the used statistical indicators are given in Table 3.

4 Results and discussion

In this section we apply the described methodology to simulations performed by the four models described in Sect. 2.3. Ten European remote sensing stations contributed data to this intercomparison, mainly concentrated in the Mediterranean area, as shown in Fig. 1. Their location and data supplied can be seen in Table 4. All stations are part of the EARLINET and AERONET networks, a fact that guarantees that the provided data are of uniform quality. The participating stations provided, in total, 61 LIRIC retrievals of dust profiles for an agreed time period of January 2011 to February 2013. The time difference between lidar and photometer measurements was kept as small as possible (72 % – < 1 h, 93 % – < 3 h). In all cases attention was given to have stable

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Our examination indicates that the simulations systematically underestimate the total amount of dust. Figure 5 presents the comparison of the dust concentration integrated across the common altitude range for each case. The volume concentration from the four models shows significant correlation with the measured one, but in general is underestimated. For high concentration cases (values greater than $\sim 0.3 \text{ g m}^{-2}$) NMMB/BSC-DUST and DREAM8-NMME-MACC predict sufficiently well the concentration values, while the other two models tend to underestimate. For low concentration values (less than 0.3 g m^{-2}) all models apart from DREAM8-NMME-MACC underestimate in many cases the dust concentration. This could be caused by insufficient dust source strength, overestimated deposition and wet scavenging parameters, or a combination of both; the current dataset is not sufficient to discriminate the exact factor affecting the comparison from the model point of view. It is believed, however, that using the present approach as part of a complete, multi-sensor evaluation exercise would help investigating possible model limitations. The improved performance of DREAM8-NMME-MACC could be attributed to the assimilation scheme used only by this model. The total fractional bias values for the models range from -1.05 to -0.25 , while correlation coefficients range from 0.52 to 0.82 .

Figure 6 shows the relationship of peak simulated values for each profile and the measured ones. Also in this case, the models underestimate the maximum value of each profile. The fractional bias for the four models ranges from -0.89 to -0.31 while the correlation coefficient has smaller values than before from 0.52 to 0.72 . This result can only partly be explained by the overall concentration underestimation that was noted before. The lower original resolution of the models, compared to the lidar, could lead to a “smoothing” effect of individual peak values in the compared cases. A similar effect could be caused by the mixing of the dust in all the volume of the model’s grid. A summary of the above described statistics for all the examined models is given in Table 5.

In summary, the current study indicates that the examined dust models represent well the altitude of transport while the total concentration is predicted lower than mea-

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



sured, with sharp peaks smoothed out. The performance of models in specific cases, however, can vary significantly. Figure 7 summarizes the performance of all models on a case-by-case comparison. For each model-measurement pair we calculate the vertical correlation coefficient of the volume concentration profiles as well as the fractional bias, and the results are plotted in a scatterplot. The ideal model would have correlation one, i.e. it would predict perfectly the shape of the dust profile, and 0 fractional bias, i.e. predicting correctly the quantity of transported dust. While individual cases show a big variability, each model shows a characteristic pattern. For BSC-DREAM8b v2 and DREAMABOL most cases have high correlation but negative fractional bias i.e. the models can often predict correctly the shape of the dust profile but underestimate the concentration. In contrast, NMMB/BSC-DUST and DREAM8-NMME-MACC have fractional bias value distribution near 0 but a wider spread of correlation values. For all models, it should be observed that there is a considerable spread of values for the specific comparisons, a further argument for the need for a statistical evaluation of dust model performance.

These results are further supported by directly comparing the profile data provided by the model, indicating that models do not only capture the general altitude of dust transport but, on average, predict correctly the shape of the dust profile. In Fig. 8 the mean measured concentration profile for all 61 cases is compared with the corresponding profiles of the four models. The profiles show good agreement in the predicted shape of the dust concentration, but have wider spread in the absolute values. BSC-DREAM8b v2 and DREAMABOL predict the maximum dust concentration in the region 2–3 km a.s.l., in agreement with the observations, while the other two models have the maximum value at slightly higher altitude of 3–4 km. DREAM8-NMME-MACC overestimates the concentration of dust in altitudes above ~ 5 km; specifically, while the observed values of dust are below $10 \mu\text{g m}^{-3}$ above 6 km, the model predicts these values only above 8 km. The concentration values show wider discrepancy: while the peak value of the mean profiles is retrieved at $\sim 65 \mu\text{g m}^{-3}$ the models peak values range from ~ 30 to $\sim 50 \mu\text{g m}^{-3}$. The observed increased concentration at high alti-

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tudes in some models could be related to misrepresentation of the tropopause (Janjic, 1994; Mona et al., 2014) that normally limits the maximum altitude of dust transport. In higher altitudes, the main removal mechanism of dust is sedimentation, and the removal of any dust reaching high altitudes is slower, allowing the artificial accumulation of dust. When examining the profile data, we can observe the differences in high and low concentration cases that were described before, as shown in Fig. 9. NMMB/BSC-DUST and DREAM8-NMME-MACC have particularly good agreement at the high concentration cases. As noted before, such findings highlight the importance of statistical comparison approach and indicate that this trend should be investigated in a future complete evaluation study.

The above results are further explored in Figs. 10–13. Figure 10 presents the mean bias of the four studied models. All models show negative bias below 4 km while above that altitude NMMB/BSC-DUST has almost 0 bias and DREAM8-NMME-MACC has positive bias values. At the altitude range where most dust is located, i.e. from 2 to 4 km a.s.l., the maximum biases range from -40 to $0 \mu\text{g m}^{-3}$. In Fig. 11 the variation of the RMSE with altitude is shown. In the 2–4 km range the mean values range from 40 to $67 \mu\text{g m}^{-3}$ with the maximum value reached by DREAMABOL at 2 km a.s.l. The profiles of correlation coefficient for the four models are shown in Fig. 12. All four models show significant correlation for altitude range from 1 to 6 km, which is the region where most dust particles are typically observed (Mona et al., 2006). The mean values range from 0.50 for DREAMABOL to 0.65 for DREAM8-NMME-MACC. Finally, in Fig. 13 the fractional gross error is shown. The minimum values for F_E , ranging from 0.77 to 1.14, are observed at 2–4 km. At higher altitudes, the F_E values are higher, with values ranging from 1.28 to 1.66 at 6 km a.s.l.

A summary of the different behavior of the four models is given in Fig. 14 using Taylor diagrams (Taylor, 2001). The data of the models and measurements were averaged at 1 km altitude ranges before calculating the statistics, to give an overview of the model performance at these regions. Four Taylor diagrams are presented, for the altitude range from 1 to 5 km. DREAM8-NMME-MACC seems to capture correctly the range of

values of the dust events in all altitude ranges, a property that can partly be attributed to the use of data assimilation. NMMB/BSC-DUST shows similar good performance, especially for 3 to 5 km. As observed before, the other two models underestimate the variability of dust in a consistent way with altitude. The model simulations have correlations from 0.4 to 0.8 at all four altitude ranges.

The presented results depend on regional and seasonal variations. While the available cases in this study are not sufficient to perform a seasonal analysis, they can be used to get a hint of the insight that can be gained from a regional evaluation of the model performance. With this aim, the available stations were divided in two clusters, a west and an east one. The west cluster of stations, including Evora, Granada, and Barcelona, is affected by dust events arriving only after a few days of transport. The east cluster, including Potenza, Lecce, Athens, Thessaloniki, and Bucharest, is affected by longer transport of dust from both the West and Central Sahara. The regional comparison of the mean dust concentration profiles is shown in Fig. 15. The average profiles indicate that the dust is transported at different altitudes, with the maximum value observed around 2 km a.s.l. for the west cluster and around 3 km a.s.l. for the east cluster, a behavior that is well captured by all models. The correlation coefficient at all altitudes is higher for the east rather than the west cluster as shown in Fig. 16. Specifically, the average correlation at the altitude range from 2 to 5 km ranges for the west cluster from 0.50 to 0.70 and for the east cluster from 0.55 to 0.87. This difference can be attributed to the strong effect of orography on the west cluster, as Atlas Mountains and orography of the Iberian Peninsula make the prediction of the dust transport difficult, while the transport to the East cluster is performed, for large part of the transport path, over the Mediterranean Sea. Additionally, the longer transport to the east cluster, typically 1–2 days longer according to back-trajectory analysis, homogenizes the dust transport event and makes small inconsistencies in space and time less relevant. These preliminary results indicate that the regional aspects in prediction of the vertical distribution of dust should be further studied.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 Conclusions

A methodology for the examination of dust model data using volume concentration profiles retrieved using the synergy of lidar and sun photometer has been presented. The proposed approach adapts previous experience from SDS-WAS to the use of dust volume concentration profiles. The methodology was applied for the examination of 4 dust models using 61 dust concentration profiles retrieved from EARLINET/AERONET station across Europe using the LIRIC algorithm.

This first comparison presented is a clear indication that the representation of dust vertical structure by dust models needs to be further explored. The four models can individually predict different aspects of dust transport, but show considerable differences in their performance despite many similarities in their setup, including the number of dust size bins and deposition processes. The reasons for these differences should be the topic of future evaluation studies including a variety of sensors, e.g. AERONET photometer and satellite AOD measurements, to explore different aspects of dust modeling systems. This is a further indication that ensemble dust models products should be considered to improve the forecast quality.

Additionally, the results presented provide indications for future developments needed in the observational infrastructure and remote sensing algorithms used. The number of available remote sensing measurement should increased to allow better characterization of regional and seasonal aspects of model performance. For this to happen, automatic retrieval algorithms and continuous operating lidar systems should be developed and used. This would also allow the near-real time evaluation of dust models, providing important feedback both to modelers and end-user communities. A further step needed from the retrieval algorithms perspective is a better characterization of the error, both at statistical and systematic level. This will allow distinguishing more subtle effect in different model setups. Such improvements are actively pursued in the framework of ACTRIS and other projects across Europe.

AMTD

8, 3605–3666, 2015

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In total we believe that this study is an important step toward the systematic use of remote sensing atmospheric profiling measurements to model-evaluation studies. The increase availability of advanced profiling data from multi wavelength lidars and sun photometers will form a solid base to improve dust model performance and lead to better understanding of the effect of dust on air-quality, weather and the climate.

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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Binietoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Binietoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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AMTD

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Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Comparison of lidar dust products for dust model evaluation.

Product	Geometrical properties	Quantitative	Mixed dust cases	Direct comparison
Range corrected signals	Yes	No	No	No
Optical products	Yes	Yes	No	No
Dust optical products	Yes	Yes	Yes	No
Dust concentration	Yes	Yes	Yes	Yes

Dust model comparison methodology

I. Biniotoglou et al.

Table 2. Summary of the main parameters of the dust transport models used in this study (adapted from Benedetti et al., 2014).

	BSC-DREAM8b v2	NMMB/BSC-DUST	DREAMABOL	DREAM8-NMME-MACC
Institution	BSC-CNS	BSC-CNS	CNR-ISAC	SEEVCCC
Meteorological driver	Eta/NCEP	NMMB/NCEP	BOLAM	NMME/NCEP
Initial and boundary conditions	NCEP/GFS	NCEP/GFS	NCEP/GFS	ECMWF
Resolution	0.33° × 0.33°	0.33° × 0.33°	0.4° × 0.4°	0.25° × 0.25°
Source mask	USGS-FAO with Ginoux et al. (2001)	USGS-FAO with Ginoux et al. (2001)	USGS-FAO with Ginoux et al. (2001)	USGS-FAO with Ginoux et al. (2001)
Emission scheme	Uplifting –Shao et al. (1993) –Janjic (1994) –Nickovic et al. (2001)	Saltation and sandblasting –White (1979) –Marticorena and Bergametti (1995) –Janjic (1994) –Nickovic et al. (2001)	Uplifting –Shao et al. (1993) –Nickovic et al. (2001)	Uplifting –Shao et al. (1993) –Janjic (1994) –Nickovic et al. (2001)
Deposition scheme	Dry deposition –Zhang et al. (2001) Below-cloud scavenging –Nickovic et al. (2001)	Dry deposition –Zhang et al. (2001) Wet deposition –Ferrier et al. (2002) –Betts (1986) –Janjic (1994)	Dry deposition –Zhang et al. (2001) In and below-cloud scavenging –Maurizi and Monti (2015) Convective clouds, precipitation and re-evaporation	Dry deposition –Zhang et al. (2001) Below-cloud scavenging –Nickovic et al. (2001)
Vertical resolution	24 Eta-layers	40 σ -hybrid layers	50 σ -hybrid layers	24 σ -hybrid layers
Transport size bins	8 (0.1–10 μ m)	8 (0.1–10 μ m)	8 (0.1–10 μ m)	8 (0.1–10 μ m)
Radiation interaction	Yes	No	No	No
Data assimilation	No	No	No	Yes

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

Table 3. Definition, symbol, value range, and ideal score for the statistical performance indicators used in the systematic examination of dust model concentration profiles. c denotes the concentration at altitude z . M_i and O_i represent modeled and observed profiles, respectively for the i th measurement pair. Altitude dependence is omitted for brevity.

Metric	Symbol	Definition	Range	Perfect score
Center of mass	CoM	$\frac{\int_{z_{\min}}^{z_{\max}} z \cdot c \cdot dz}{\int_{z_{\min}}^{z_{\max}} c \cdot dz}$	–	–
Mean Bias	MB	$\frac{1}{N} \sum_{i=1}^N (M_i - O_i)$	$-\infty$ – ∞	0
Correlation coefficient	r	$\frac{\sum_{i=1}^N (M_i - \bar{M})(O_i - \bar{O})}{\left[\sum_{i=1}^N (M_i - \bar{M})^2 \sum_{i=1}^N (O_i - \bar{O})^2 \right]^{\frac{1}{2}}}$	–1–1	1
Root Mean Square Error	RMSE	$\left[\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2 \right]^{\frac{1}{2}}$	0– ∞	0
Fractional Bias	F_B	$\frac{2}{N} \sum_{i=1}^N \left(\frac{M_i - O_i}{M_i + O_i} \right)$	–2–2	0
Fractional Gross Error	F_E	$\frac{2}{N} \sum_{i=1}^N \left \frac{M_i - O_i}{M_i + O_i} \right $	0–2	0

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

Table 4. The following 10 stations provided dust concentration profiles retrieved by the LIRIC algorithm. Three measurements of the Evora station do not include depolarization information. The provided references give further information for each station and the measurement instruments.

Station	Location (° N, ° E)	Altitude (m)	Lidar channels	No. Profiles	Reference
Athens	37.97, 23.77	212	3β	3	Kokkalis et al. (2012)
Barcelona	41.39, 2.17	115	3β	8	Kumar et al. (2011a)
Belsk	51.84, 20.79	180	3β	1	Pietruczuk and Chaikovsky (2012)
Bucharest	44.35, 26.03	93	3β + 1δ	5	Nemuc et al. (2013)
Evora	38.57, -7.91	293	3β + 1δ*	18	Preißler et al. (2011)
Granada	37.16, -3.61	680	3β + 1δ	8	Guerrero-Rascado et al. (2009)
Lecce	40.30, 18.10	30	3β + 1δ	4	Perrone et al. (2014)
Leipzig	51.35, 12.43	90	3β + 1δ	3	Althausen et al. (2009)
Potenza	40.60, 15.72	760	3β + 1δ	8	Madonna et al. (2011)
Thessaloniki	40.63, 22.95	60	3β	3	Papayannis et al. (2012)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

Table 5. Correlation coefficient (r) and fractional bias (F_B) for single value metrics of the compared profiles.

	Center of Mass		Total concentration		Peak value	
	r	F_B	r	F_B	r	F_B
BSC-DREAM8b v2	0.60	0.01	0.74	-0.90	0.69	-0.88
NMMB/BSC-DUST	0.79	0.16	0.82	-0.76	0.70	-0.76
DREAMABOL	0.72	0.01	0.52	-1.05	0.52	-0.89
DREAM8-NMME-MACC	0.79	0.13	0.77	-0.25	0.72	-0.31

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

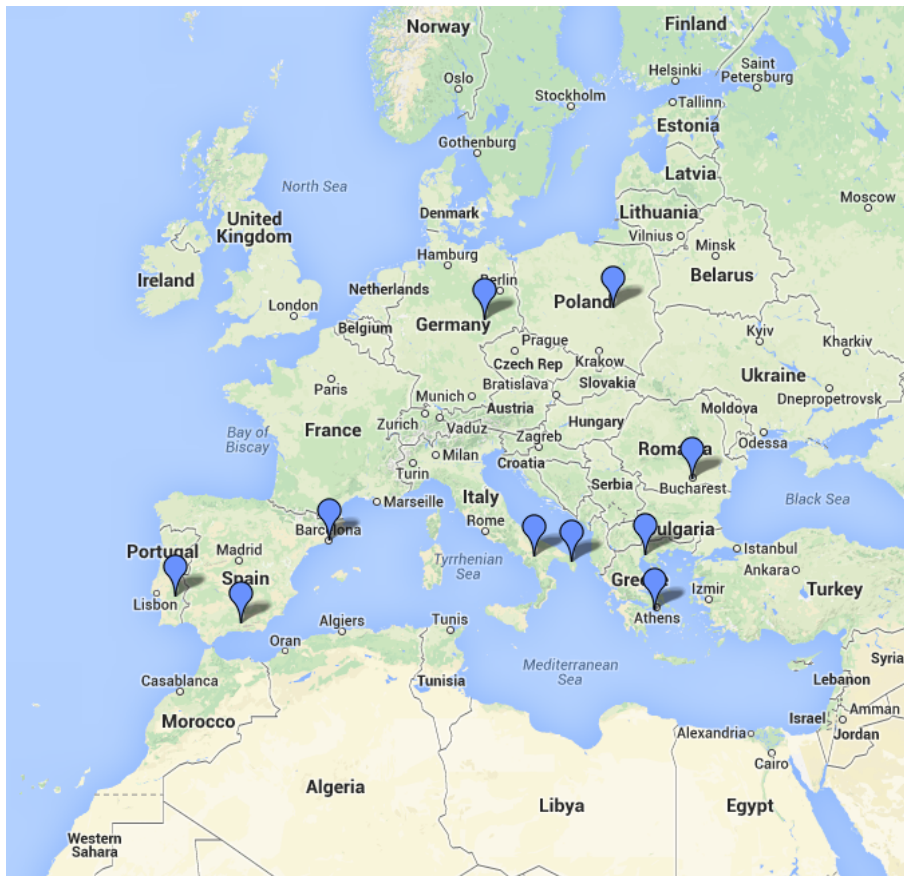


Figure 1. Map of the ACTRIS/EARLINET remote sensing stations providing data for testing the proposed methodology.

Dust model comparison methodology

I. Biniotoglou et al.

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



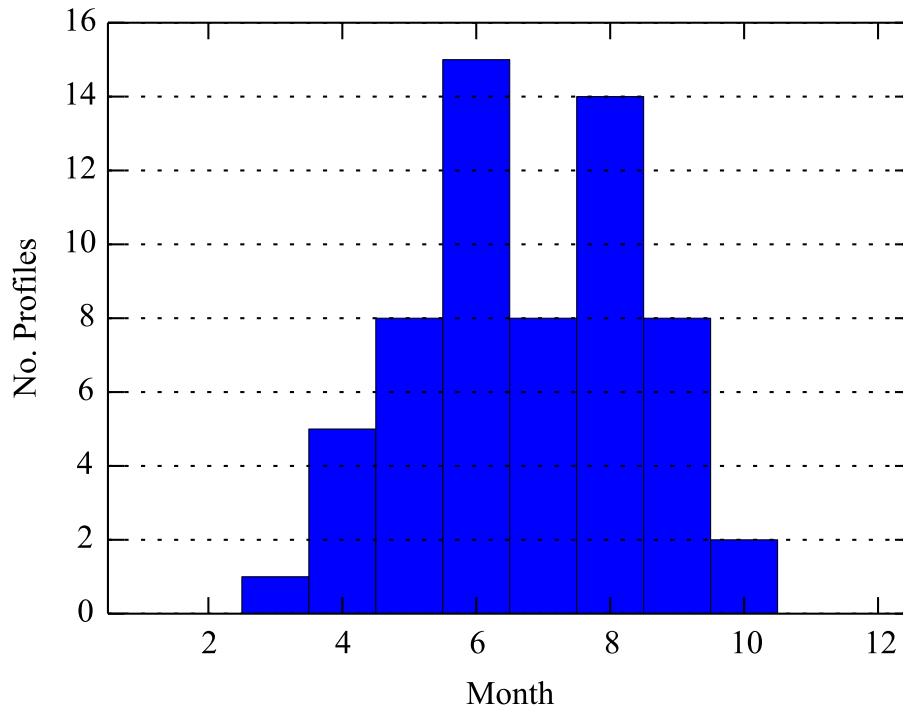


Figure 2. Distribution of available measurements per month.

Dust model comparison methodology

I. Biniotoglou et al.

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



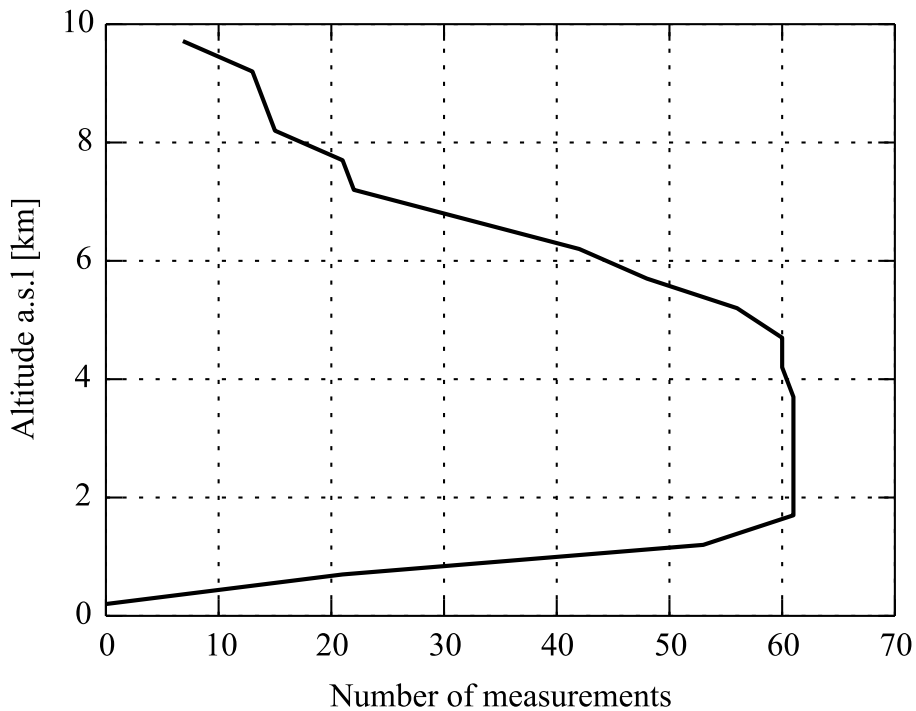


Figure 3. Number of used remote sensing profiles per altitude.

Dust model comparison methodology

I. Biniotoglou et al.

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



**Dust model
comparison
methodology**

I. Biniotoglou et al.

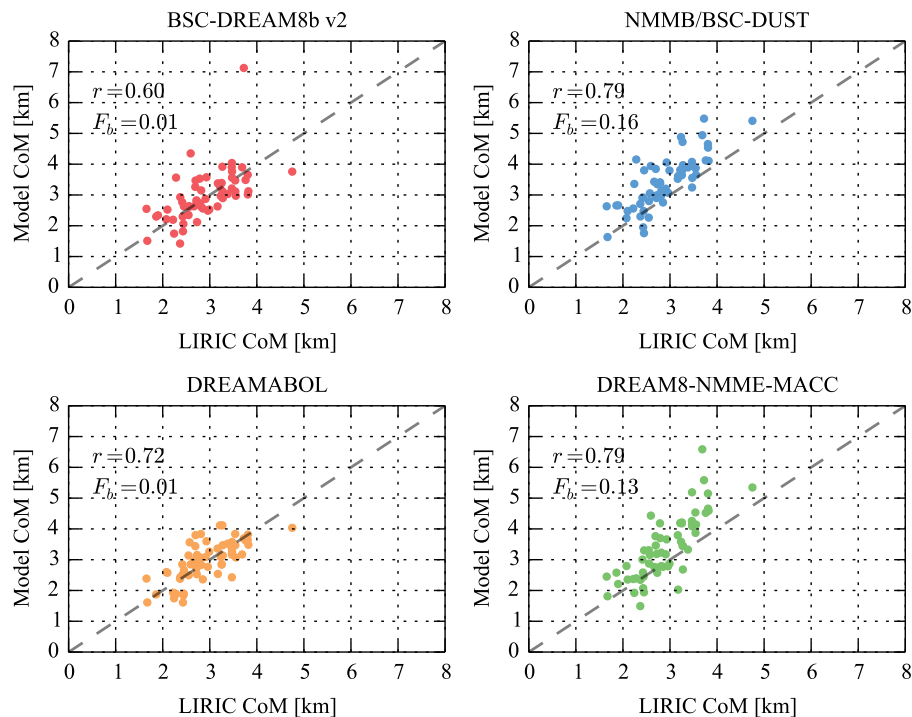


Figure 4. Comparison of dust center of mass for the four models against the ones retrieved from LIRIC.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

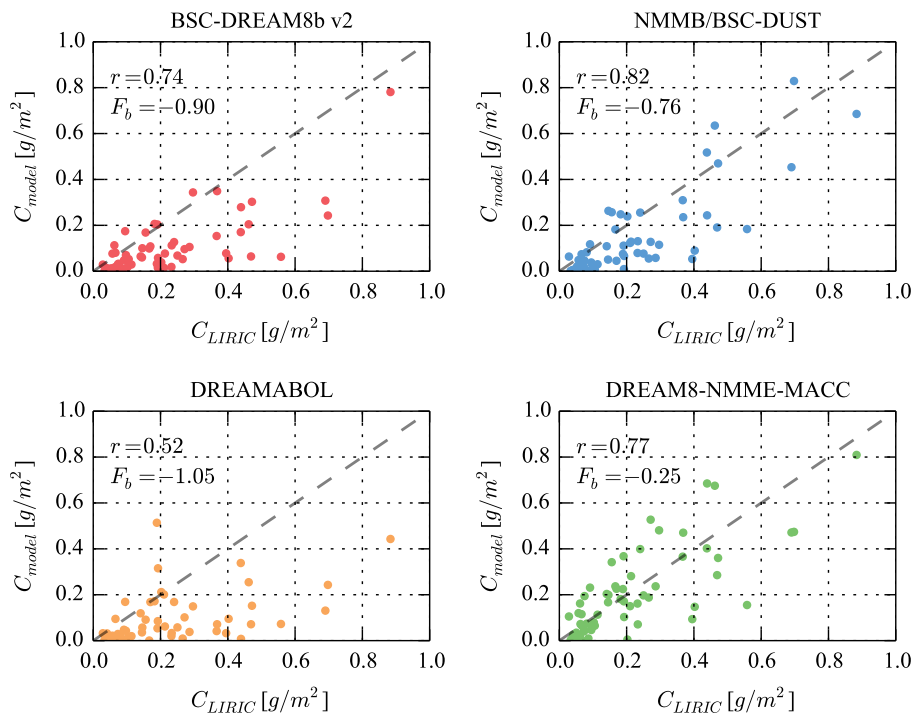


Figure 5. Comparison of integrated dust concentration for the four models against the ones retrieved from LIRIC. The value is calculated only for the altitude ranges for which both models and measurements provide valid values.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

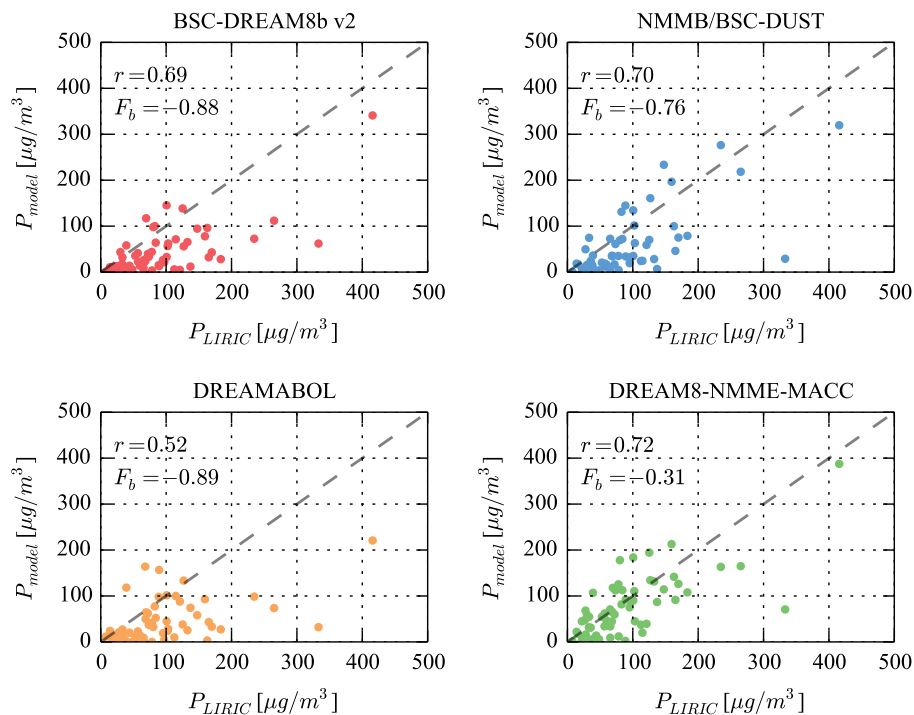


Figure 6. Comparison of profile peak value for the four models against the ones retrieved from LIRIC.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model
comparison
methodology

I. Biniotoglou et al.

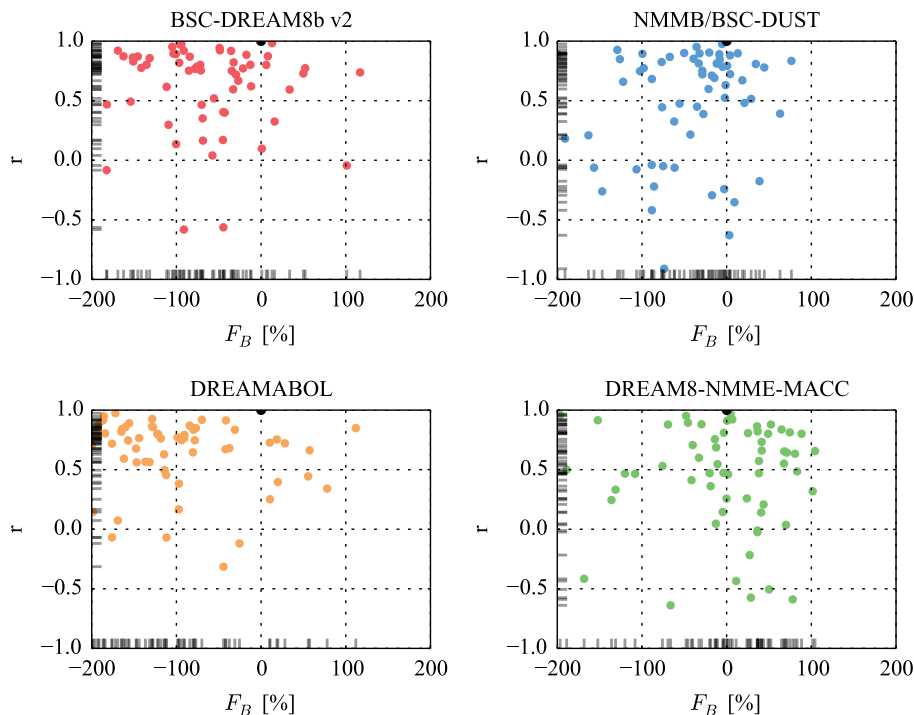


Figure 7. Scatter plot of vertical correlation and fractional gross error. Black dots represent the ideal performance (0, 1). Each point on the plot corresponds to a pair consisting of one LIRIC and one model profile. The bars on the axis indicate the univariate distribution of the data for each variable.

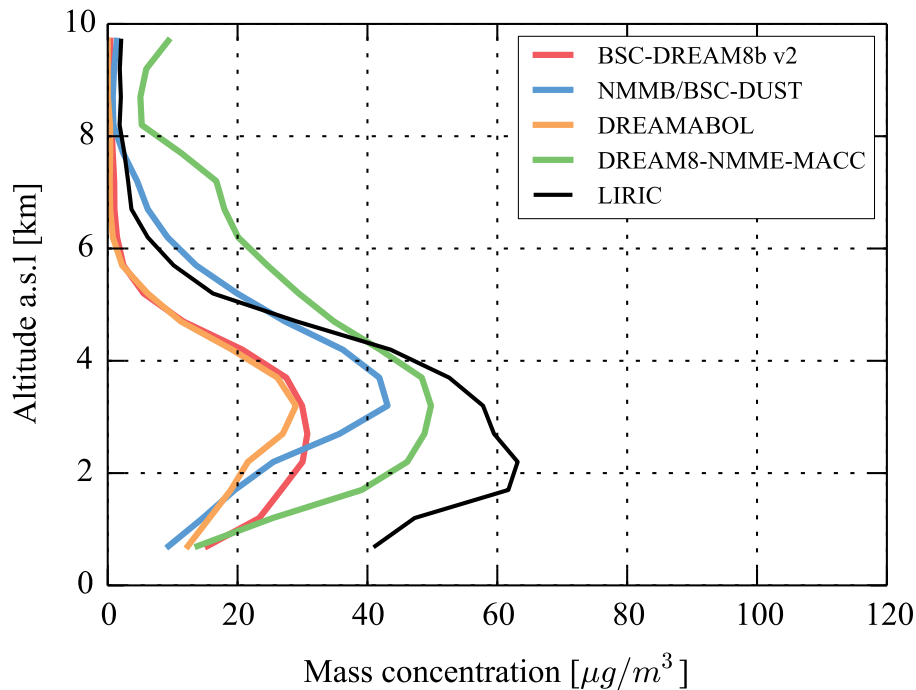


Figure 8. Average profile comparison as simulated by four model and retrieved by LIRIC.

Dust model comparison methodology

I. Biniotoglou et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

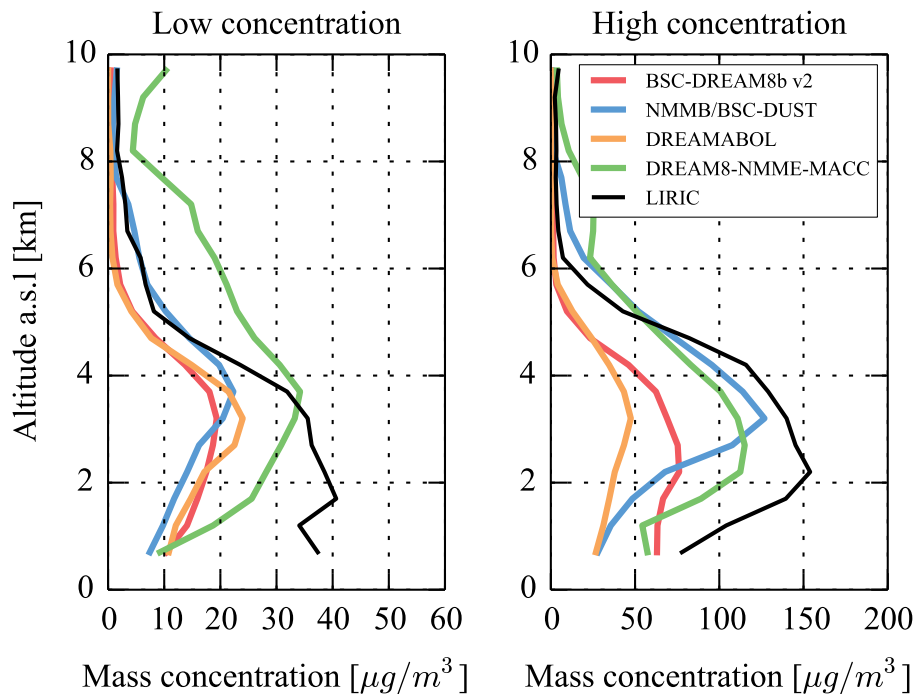


Figure 9. Comparison of average profiles simulated by all four model for low and high concentration cases, separated at 0.3 g m^{-2} .

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



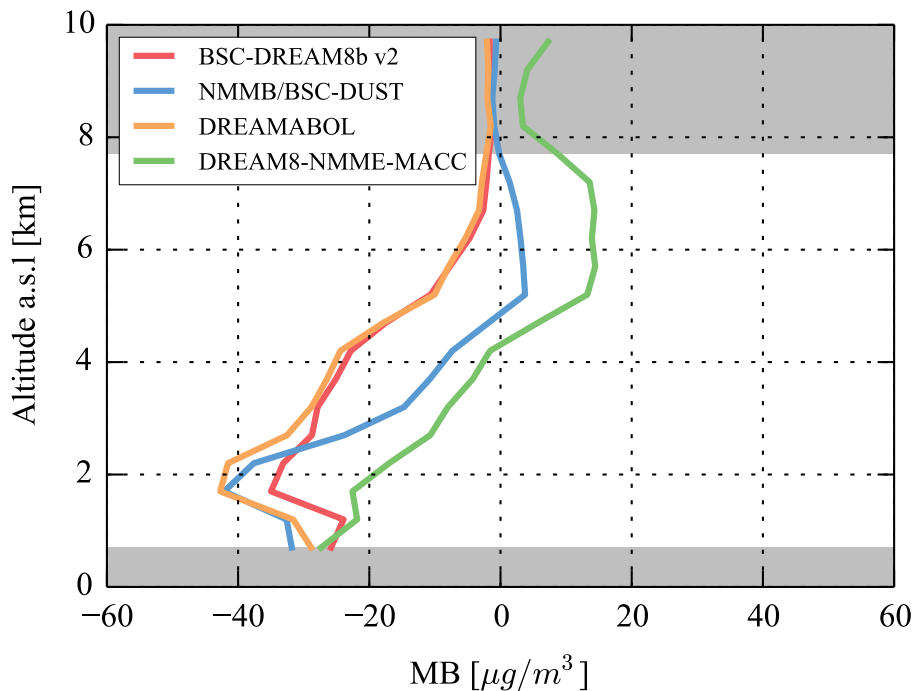


Figure 10. Profiles of mean bias error for all four models. Gray shading indicates altitude ranges with less than 20 profiles available.

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



Dust model comparison methodology

I. Biniotoglou et al.

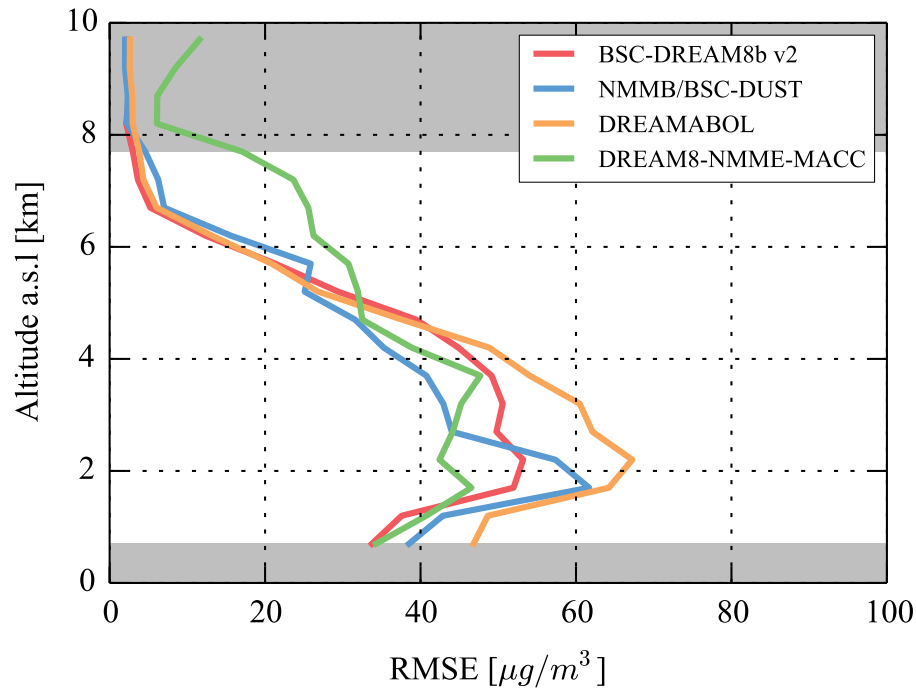


Figure 11. Profiles of root mean square error for all four models. Gray shading indicates altitude ranges with less than 20 profiles available.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



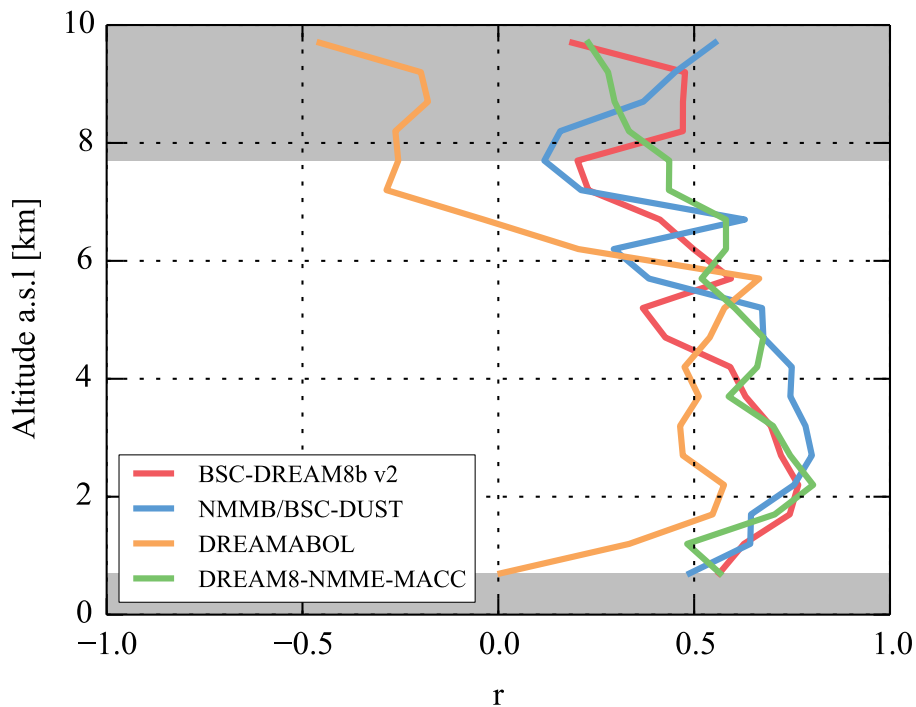


Figure 12. Profiles of correlation coefficient r for all four models. Gray shading indicates altitude ranges with less than 20 profiles available.

Dust model comparison methodology

I. Biniotoglou et al.

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



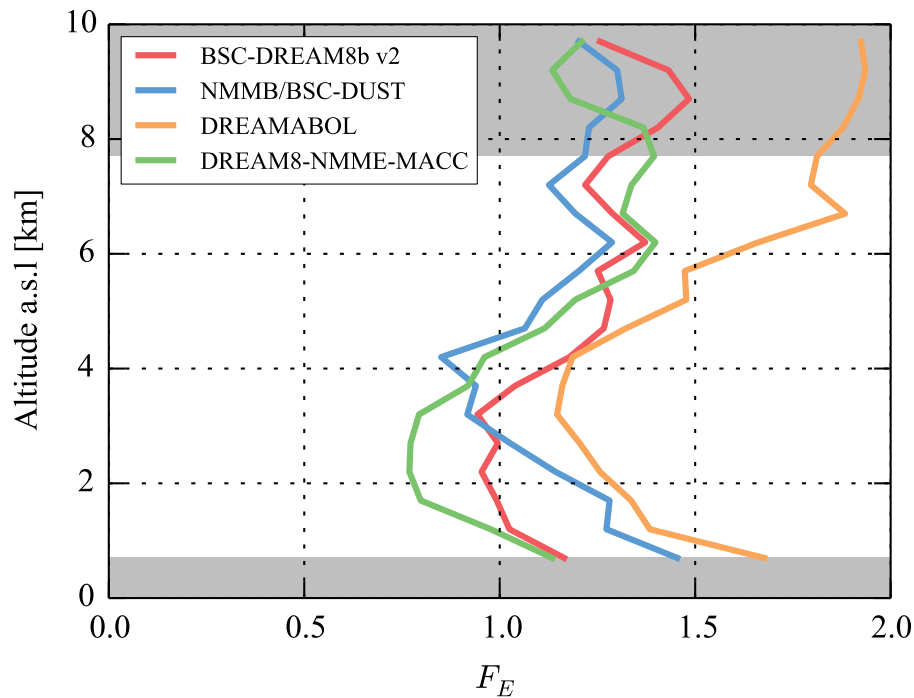


Figure 13. Profiles of fractional gross error r for all four models. Gray shading indicates altitude ranges with less than 20 profiles available.

Dust model comparison methodology

I. Biniotoglou et al.

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



Dust model comparison methodology

I. Biniotoglou et al.

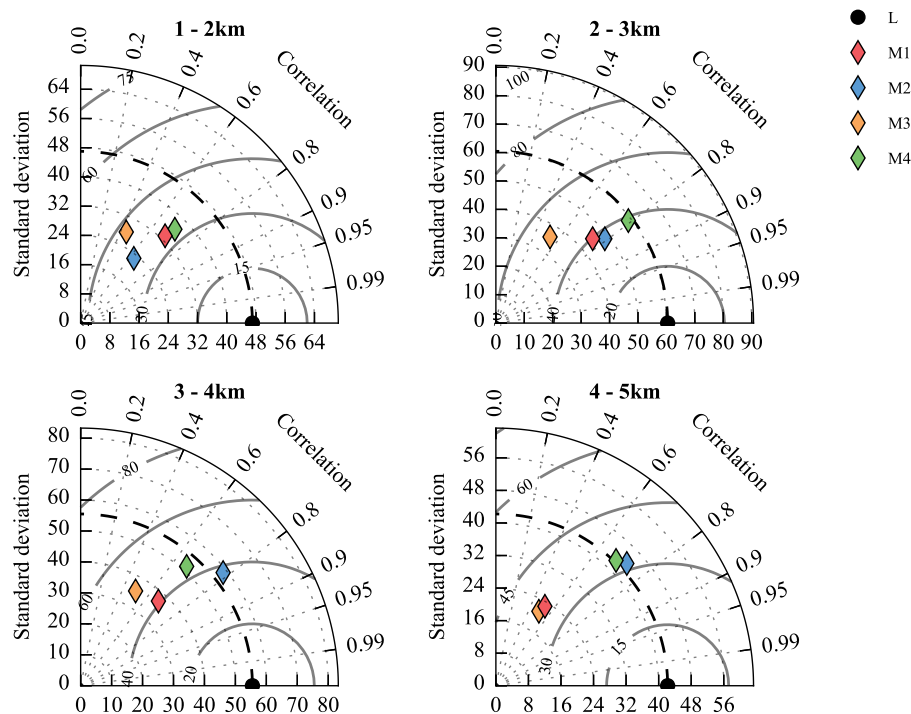
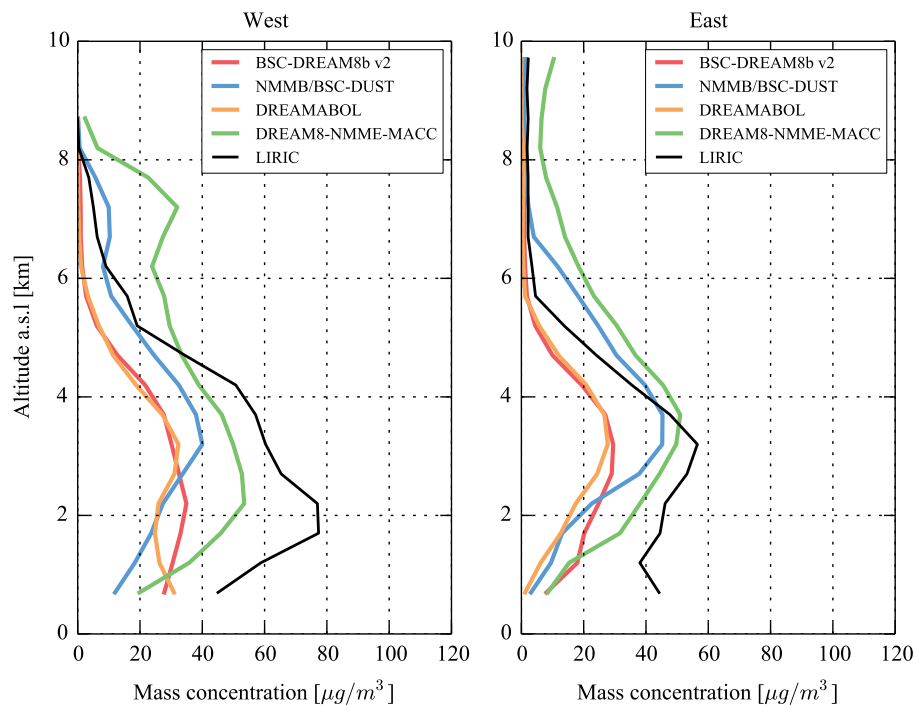


Figure 14. Taylor's diagrams for four different altitude ranges, from 1 to 5 km. The black dots represent the observational data. The distance of any point from the origin indicates the SD of the dataset. The angular distance of a point from the horizontal axis indicates the correlation of model and measured data. The distance of two points in these plots is proportional to their centered root mean square (RMS) difference. L: LIRIC observations, M1: BSC-DREAM8b v2, M2: NMMB/BSC-DUST, M3: DREAMBOL, M4: DREAM8-NMME-MACC.

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


Dust model comparison methodology

I. Biniotoglou et al.

**Figure 15.** Comparison of mean concentration profiles for the west and east station clusters.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dust model comparison methodology

I. Biniotoglou et al.

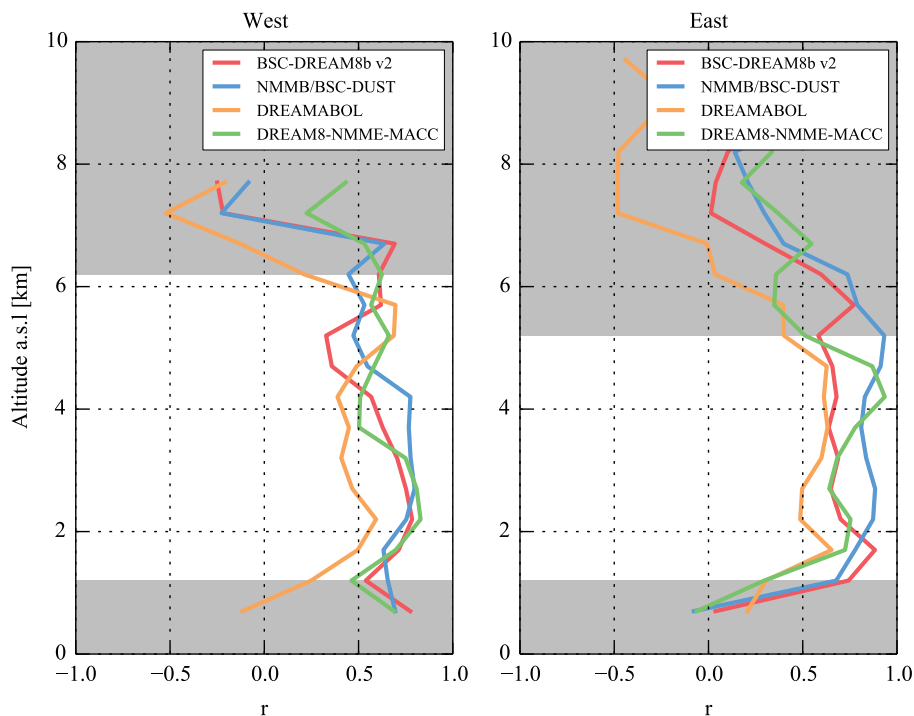


Figure 16. Comparison of correlation coefficient profiles for the west and east station clusters. Gray shading indicates altitude ranges with less than 20 profiles available.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

