Model initialization and validation with ground- and space-based lidar measurements

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ABSTRACT

The regional aerosol transport model system COSMO-MUSCAT in its standard setup is initialized by vertical profiles of chemical substances as well as aerosol particles at the lateral boundaries of the European model domain. In the study presented here, lidar profiles of aerosol backscatter and sunphotometer data are used to initialize vertical distribution of primary particles ($\mathrm{PPM}_{2.5}$) at the model boundaries. We compare model results for several case studies, initializing the model with: (1) climatological average profiles from EARLINET lidar stations near the model boundaries, averaging measurements for periods when air masses entering the model domain were clean; and (2) individual profiles from EARLINET stations in Europe, at the day preceding the model start. We also use (3) lidar profiles from the CALIPSO satellite to provide initial profiles of $\mathrm{PPM}_{2.5}$ as input at the boundaries of the model domain. In addition, (4) AERONET data from stations near the model boundary were used as boundary information. For all calculations, EARLINET and CALIPSO lidar profiles that are not taken as model input are used to evaluate the simulated extinction profiles for the different model cases.

1. INTRODUCTION

The recently published IPCC report demonstrates the large uncertainty in the determination of direct and indirect radiative forcing of climate by anthropogenic tropospheric aerosol [1].
An estimate of aerosol forcing by means of satellite measurements was published by [2]. Although data from several instruments were used assumptions regarding the aerosol properties were necessary. It was clearly shown by [3, 4] that these assumptions do not allow the classification of aerosol from natural or anthropogenic sources.
Data from remote sensing, measurements of aerosol optical depth (AOD) or measurements of physiochemical aerosol properties at the surface can not represent the large spatiotemporal variability of aerosol properties. Good agreements between AOD measurements and model simulations can result in large differences for aerosol forcing estimations as it was shown during the global model intercomparison study AeroCom (Aerosol Comparisons between Observations and Models) [5, 6].
The knowledge of the vertical distribution of atmospheric particles and their properties can help to constrain aerosol properties but cannot be fully characterized by measurements at the surface or of the AOD. By means of lidar profiling aerosol distribution and properties can be characterized, e. g. [7, 8, 9, 10].
Comparisons of simulated annual average vertical aerosol profiles and lidar measurements were performed within the AeroCom framework and published by [11]. It was shown that changes within the boundary layer are difficult to represent by a global model. On this account regional studies offer the possibility to directly evaluate individual aerosol profiles by comparing with lidar profiles and therefore better the understanding of direct aerosol effects for specific regions.
By means of the regional model COSMO-MUSCAT (COSMO: Consortium for Small-scale Modeling; MUSCAT: MultiScale Chemistry Model) a case study to characterize the European aerosol distribution was performed. The vertical distribution of chemical substances, described at the model boundaries, was adjusted according to backscatter profiles from ground- and space-based measurements (performed by CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation; [12]) as well as AOD data. Comparisons with lidar profiles from EARLINET (European Aerosol Research Lidar NETwork) stations and CALIPSO and sun photometer measurements from European AERONET (Aerosol Robotic Network; [13]) stations were used to get information about aerosol properties.

2. MODEL SETUP

COSMO-MUSCAT was used to perform the model simulations. COSMO (former LM: Lokal Modell) is the operational, non-hydrostatic meteorological model developed by the DWD [14] and online coupled with MUSCAT [15]. MUSCAT describes the atmospheric transport and vertical distribution of chemical compounds. Transport processes are sedimentation, wet and dry diffusion, advection and turbulent diffusion.
All results shown here apply to a model domain of 40 vertical layers, a horizontal grid resolution of 28 km, and the lower left corner is placed at 10.1°W and 27.5°N (156 grid cells in eastern and 136 grids in northern direction).

© Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2
Delft, The Netherlands, October 2009. Editors, A. Apituley, H.W.J. Russchenberg, W.A.A. Monna

The most common European aerosol types (urban and continental) were simulated by the model. The fraction of elemental carbon (EC) on primary particulate matter ($\mathrm{PPM_{2.5}}$) was determined in MUSCAT. For EC fraction $\geq$ 20% the particle mass was classified as urban, whereas a lower fraction was classified as continental aerosol type. The radiatice impacts of urban and continental aerosol concentrations on meteorology were simulated.

To characterize the aerosol entering the model domain, vertical profiles of particle loads are defined at the model boundaries. Four possibilities of changing these profiles are presented here:

(1) Climatological Mean

As first approach a mean climatological lidar profile (Case (1)) was used. Based on several measurements during a summer period in 2001 in Aberystwyth a mean backscatter profile (at 355 nm) was determined [16]. Based on this profile the vertical profile at all 4 model boundaries was described by two layers: First layer from bottom to 700 m, second layer (with decreasing particle load) from 700 m to 2000 m. Weighting factors (East: 2.0, South: 1.0, West: 0.6, North: 0.6) were used to influence these profiles.

(2) Individual Lidar Profiles

For the second approach individual lidar backscatter profiles, measured at EARLINET stations at the 17th of July 2006 (model simulations started at the 18th), were taken as boundary information (Case (2)). Three stations provided lidar profiles (Thessaloniki (13:35), Belsk (12:06, 18:27) and Minsk (16:06)). These 4 profiles were averaged to one vertical profile. In contrast to case (1) the extension of the first layer was larger (from bottom to 2000 m) with a constant particle load. The second layer was prescribed from 2000 m to 4000 m with stepwise decreasing load. The weighting factors for each boundary are the same like in Case (1).

(3) CALIPSO Profiles

Based on EMEP (European Monitoring and Evaluation Programme) data the vertical load for several chemical substances dependent on latitude, longitude and day of the year can be determined. Therefore for each boundary grid cell defined vertical profiles could be used. Additionally, CALIPSO profiles (Lidar Level 2, Version Releases 2.01) were used to calculate a mean backscatter profile for each boundary and therefore to adjust the former profile (Case (3)). In contrast to case (1) and (2) the vertical profiles at each boundary differ from day to day.

(4) AERONET Data

At a forth approach, data from sun photometer measurements at European AERONET stations were used as boundary input data (Case (4)). Again, backscatter profiles from lidar measurements one day before the model simulation starts (as described in Case (2)) were used. A comparison of AOD measured by near-boundary stations and simulated AOD (a run with untouched boundaries was performed) was done for every day of model simulation. A mean ratio for each model boundary was calculated and used as new weighting parameters (South = 1.06, East=0.53, West=1.03, North=0.43).

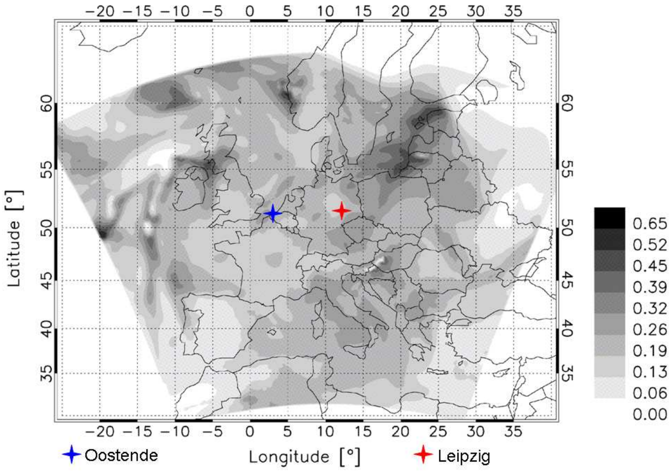

Figure 1. Model simulation of AOD over Europe for the 24th of July 2006 at 12 UTC. Model results of Case (4) are shown.

3. RESULTS

Different model simulations (case (1), (2), (3) and (4)) were performed from 18th to 26th of July 2006. During this period an anticyclone was situated over Europe over a long time. Additionally, several lidar measurements at EARLINET stations were performed during this time. Backscatter profiles of CALIPSO measurements and AOD from European AERONET stations are also available. Results for the 24th of July 2006 are shown here.

Based on chemical substances the extinction coefficient of aerosol particles was calculated at every place for every time from concentrations and mass extinction efficiencies (MEE). Different values for MEE were used for EC, $\mathrm{PPM_{2.5}}$, $\mathrm{H_2SO_4}$, $\mathrm{NH_4NO_3}$ and $\mathrm{(NH_4)_2SO_4}$, which were the most important substances for further calculations. MEE values for these model simulations are: $\mathrm{MEE_{EC}}$ = 14 $\mathrm{m^2g^{-1}}$ (EC), $\mathrm{MEE_{su}}$ = 10.2 $\mathrm{m^2g^{-1}}$ ($\mathrm{H_2SO_4}$ and $\mathrm{(NH_4)_2SO_4}$), $\mathrm{MEE_{nitr}}$ = 4.0 $\mathrm{m^2g^{-1}}$ ($\mathrm{NH_4NO_3}$) and $\mathrm{MEE_{ppm}}$ = 8 $\mathrm{m^2g^{-1}}$ ($\mathrm{PPM_{2.5}}$),selected from the wide range of MEE values [6, 5].

Based on the simulated extinction coefficients and the layer depths the aerosol optical depth (AOD) was calculated. Exemplary, the AOD is shown for Case (4) (Figure 1). For whole Europe a maximum value of 0.65 is reached. Highest values are found over the easters part of the Baltic Sea, at the westcoast of Norway and over parts of the Atlantic Sea. The lowest values are at the nort-eastern boundaries as well as over large areas of Spain. In that case, high AOD values are mainly caused by high concentrations of $\mathrm{H_2SO_4}$ and $\mathrm{(NH_4)_2SO_4}$, whereas low values of AOD are generally caused by low concentrations of EC, $\mathrm{PPM_{2.5}}$, $\mathrm{(NH_4)_2SO_4}$ and $\mathrm{H_2SO_4}$. Concentrations of $\mathrm{NH_4NO_3}$ are neglible at near surface layers but at higher altitudes the amount increases and there the contribution to AOD grows .

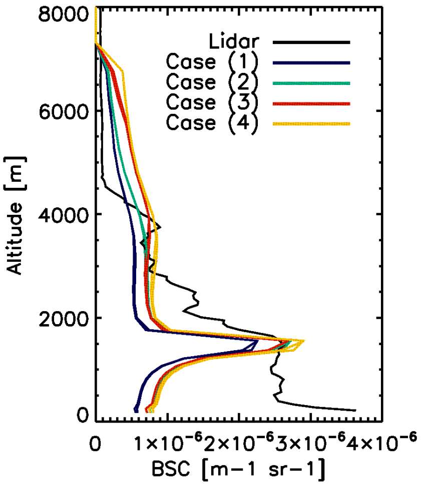

Figure 2. Comparison of measured backscatter profile (black) at EARLINET station in Leipzig with results of case (1) (blue), case (2) (green), case (3) (red) and case (4) (yellow) at 24th of July 2006, 01:30.

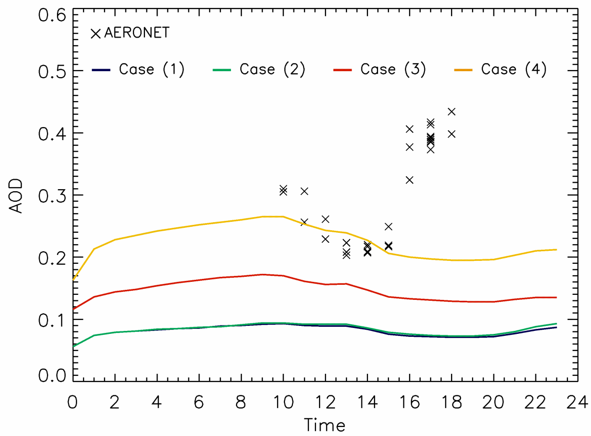

Figure 3. Comparison of measured AOD (black cross) at AERONET station Oostende, results of case (1) (blue line), case (2) (green line), case (3) (red line) and case (4) (yellow line) at the 24th of July 2006.

Comparisons of modeled backscatter profiles with lidar measurements from the EARLINET network was performed for 6 stations. Here, an example for the station in Leipzig (12.4°N, 51.4°E) is shown (Figure 2). The backscatter coefficients are calculated by means of the extinction coefficient and the lidar ratio (LR). For the case, shown here, a LR of 50 sr was chosen.
The lidar measurement was performed at the EARLINET station in Leipzig at the 24th of July 2006 at 01:30 pm. In general, the agreement between measurement and all four simulations is satisfying. No simulation is able to represent the very strong boundary layer, indicated by the lidar. The strong backscatter signal at $\approx$ 1.8 km height was reproduced by all model cases, in which Case (2) and (3) shows best agreement, whereas Case (4) slightly overestimates and Case (1) underestimates the measurement. The decreasing backscatter with increasing height is represented by all cases, although not strongly enouhg. At altitudes higher than 4 km the difference between the simulations show too high backscatter compared to the observation, especially for Cases (3) and (4).
Comparisons of modelled AOD with measurements at sun photometer stations were performed for 35 stations. An example for the results is shown in Figure 3 and refers to the sun photometer measurement at the AERONET station in Oostende (2.9°N, 51.2°E). Next to the measured AOD (black cross) the simulated AOD's for every hour are presented. Case (1) and (2) underestimate the measured AOD stronger than Case (3), whereas the results of Case (4) are satisfying. The slight decrease of AOD between 12 and 14 UTC is good represented by Case (4) and also by Case (3). On the other hand, none of the four simulations is able to reproduce the sudden and strong increase of AOD at 15 UTC. Comparisons at several other AERONET stations and at different days show nearly the same results as presented in Figure 3. In general, simulations with Case (4) agree best with measurements, but there are also cases of better results performed by Case (2) and (3) (not shown here), whereas Case (1) often underestimates the AERONET measurements. While none of the prescribed boundary conditions leads to perfect agreement with measurements, the results show that better agreement with observations is achieved for prescription of boundary values with measurements.
The examples, shown here, are a presentation of general simulation results. In general, simulations performed with actual data, like it was done in Case (2), (3) and (4), are more successful than simulations using climatological means. Model simulation and AOD observation generally agree but none of the published cases is able to reproduce strong daily variations, like it was shown in Figure 3. Representation of vertical backscatter coefficients are still difficult, whereas the comparison, shown here (Figure 2) is one of several satisfying results.

4. CONCLUSION

Four model simulations were performed with the regional model COSMO-MUSCAT. The difference between these model versions is the information at the model boundaries. The first approach uses a climatological mean of lidar profiles (Case (1)), whereas the second case uses backscatter profiles of lidar measurements performed one day before the model simulation starts (Case (2)). Based on measurements at EMEP stations, actual data could be used and were adjusted by daily CALIPSO profiles (Case (3)). In contrast to Case (1) and (2) the data were specified for each latitude, longitude and day of the year. Data from

AERONET stations were used as boundary information for the fourth simulation (Case (4)). All simulations were performed from 18th to 26th of July 2006. A comparison of simulated backscatter profiles with a measured profile from the EARLINET station in Leipzig shows the difficult task of vertical profile determination. In general, the simulation results are satisfying, showing no strong difference to the measurement profile. Simulation with individual lidar profiles and CALIPSO profiles show best agreement. All model simulations have difficulties to represent the strong boundary layer. When comparing the model results with AOD from AERONET stations best agreement was for Case (4). Simulations with climatological mean profiles and individual lidar profiles underestimated the measurements stronger than Case (3). Data delivering daily information about the atmospheric conditions, like lidar measurements performed by CALIPSO and sun photometer measurements performed by AERONET stations, a high potential of model development is given. Further model simulations during different time periods shall give more information about the application of presented case studies.

ACKNOWLEDGMENTS

The EARLINET data from Minsk, Thessaloniki, and Belsk have been provided by Anatoli Chaikovsky (Institute of Physics National Academy of Sciences, Minsk, Belarus), Elina Giannakaki (Aristotle University of Thessaloniki, Greece), and Piotr Sobolewski(Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland). CALIPSO data have been provided by the Atmospheric Sciences Data Center (ASDC).

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