

NOTES AND CORRESPONDENCE

An Observing System Simulation Experiment (OSSE) for Aerosol Optical Depth from Satellites

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ABSTRACT

Monitoring aerosols over wide areas is a scientific challenge with important applications for human health and the understanding of climate. Aerosol optical depth (AOD) measurements from satellites can improve the highly needed analyzed and forecasted distributions of ground-level aerosols in combination with models and ground-based measurements. To assess the benefit of future satellite AOD measurements, an observing system simulation experiment (OSSE) is developed. In this pilot study, the OSSE is applied to total AOD measurements from a flexible combined imager (FCI) proposed to fly on a geostationary satellite. OSSEs are widely used in the meteorological research community, but their use for air quality applications and specifically for aerosols is new. In this paper, the functionality and potential of the developed OSSE for evaluation of aerosol data from future satellite missions are demonstrated. The results show a positive impact of adding AOD observations next to in situ observations for the analysis of PM_{2.5} (particles smaller than 2.5 μm in median diameter) distributions. However, the development of an OSSE for aerosols presents a number of further challenges, as discussed in this paper, which prohibits a detailed quantitative analysis of the results of this pilot study.

1. Introduction

Aerosols play an important role in the earth's radiation budget and the climate system through their interaction with clouds and solar radiation (Kiehl and Briegleb 1993). Also, health studies have shown that short- and long-term exposure to aerosols has a negative effect on human health and can lead to premature death (Brunekreef and Holgate 2002). To protect against the negative health effects, the European Union (EU) and the United States (US) have set limit values for particulate matter loadings. Furthermore, the EU member states have an obligation to inform the public on the

actual air quality situation. Hence, there is a need for accurate analyzed and forecasted distributions of aerosol concentrations.

Traditionally, in situ ground-based measurements are used to provide information on aerosol concentrations. However, these have the disadvantage of a low spatial coverage and measurement methods and correction factors are sometimes not consistent between different countries. Spaceborne observations of aerosol optical depth (AOD) have the advantage of providing full spatial coverage (although only during daylight and cloud-free conditions) and—in principle—consistent data for the whole European region. Thus, synergetic use of satellite measurements, models, and ground-based measurements may be useful to improve the insight into aerosol distributions in Europe. Assimilation experiments, in which satellite data have been combined with models, have shown that current satellite data have

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a positive influence on the determination of the aerosol distribution, but the capability of the assimilation systems to track the evolution of the aerosol distributions is still limited because of the large time intervals (one day or longer) between valid retrievals (Schaap et al. 2006). Hence, a higher temporal resolution of the AOD data may be highly beneficial.

User consultations (Lelieveld 2003; EUMETSAT 2006) as well as the projects Protocol Monitoring for the Global Monitoring for Environment and Security (GMES) Service Element (PROMOTE) and Composition of the Atmosphere: Progress to Applications in the User Community (CAPACITY; Goede 2005) have led to resolution requirements for future AOD derived from spaceborne observations intended to be used for air quality applications. The required high temporal resolution and quality present a challenge for instrument design. To consolidate these requirements with respect to spatial and temporal resolution, an observing system simulation experiment (OSSE) is developed, a concept that has commonly been used in meteorology for testing the impact of future spaceborne measurements (Masutani et al. 2006) but never in atmospheric chemistry for aerosol measurements. In this paper, the setup of the OSSE directed at aerosols and its application to a proposed future instrument [the flexible combined imager (FCI)] that will measure total AOD columns from a geostationary satellite are presented. The issues encountered during this first application of the OSSE principle to aerosol retrievals are discussed. Some results are shown demonstrating the potential of the OSSE system for such applications. However, the encountered issues do not allow an extensive quantitative evaluation of results and consolidation of the requirements.

2. Observing system simulation experiments

Generally, observing system experiments (OSEs) are used to assess the impact of existing operational observing systems on, for example, weather forecasts. These experiments contain the following elements:

- a state-of-the-art model,
- active data assimilation of the observations in the model, and
- assessment of the added value of assimilation of the measurements (on, e.g., analyzed fields or forecasts).

In OSSEs, which are used to anticipate the effect of future instruments, the existing observations are replaced by synthetic observations. The synthetic measurements are generated through a so-called nature run, which is supposed to simulate the “true” state of the atmosphere.

Synthetic observations are created corresponding to instrument characteristics.

An OSSE thus consists of the following elements:

- 1) production of synthetic observations through
 - (i) a nature run performed by a state-of-the-art model (referred to as the nature run model) providing the true state of the atmosphere and
 - (ii) conversion of nature run output to synthetic observations corresponding to instrument studied by OSSE;
- 2) a state-of-the-art model different from the one in the nature run (referred to as the assimilation model);
- 3) active data assimilation of the synthetic observations in the assimilation model; and
- 4) assessment of the added value of assimilation of the measurements (on, e.g., analyzed fields or forecasts) through comparison of resulting fields with the true state of the atmosphere (i.e., the nature run output).

The nature run model used to generate the synthetic observations should differ from the assimilation model in which the observations are assimilated. The differences should ideally approximate the differences between a state-of-the-art model and the real atmosphere. In an OSSE, analyzed fields and forecasts are evaluated by comparing with the “truth” represented by the nature run.

3. Model system

The model used in this study is the Long Term Ozone Simulation–European Operational Smog (LOTOS-EUROS) model, a three-dimensional Eulerian chemistry transport model of intermediate complexity (Schaap et al. 2008). The model covers the European region and is aimed to describe air pollution in the lower troposphere (up to 3.5–5 km above sea level). Because during 90% of the time, 90% of all aerosols are below about 3 km, the limited vertical extension of this model version is adequate for the current study. In the vertical, the system has four layers that use the dynamic mixing layer approach. The first layer is a fixed surface layer of 25 m, the second layer follows the mixing layer height, and layers three and four are equally thick, covering the altitudes between the mixing layer height and the top of the model at 3.5 km. The standard horizontal resolution is 0.25° latitude \times 0.5° longitude, approximately $30 \text{ km} \times 25 \text{ km}$ (depending on the latitude), with the possibility to increase the resolution up to a factor of 8. The model contains all relevant processes, although mostly in parameterized forms to avoid exceedingly long computing times. Prior applications of the model to aerosols have been documented in literature (e.g., Schaap et al.

2004; Robles González et al. 2003). The performance of the model with respect to aerosol distributions is comparable to the performance of other European chemistry transport models (see, e.g., Vautard et al. 2007). A description of the model, including chemical mechanism, emissions, meteorological input, and the latest developments, is presented in Schaap et al. (2008).

In this study, the ensemble Kalman filter technique (Evensen 1997) is used for the assimilation of observations in the model. Data assimilation basically defines a new atmospheric state by making a weighted average of the observed and modeled state using the uncertainties in both observations and model. In the ensemble Kalman filter technique, the uncertainty in the model is taken into account by applying noise factors to certain key parameters and input data of the modeling system. In this study, the noise factors have been applied to emissions, boundary conditions, and dry deposition velocity because they are thought to be the most important sources of uncertainty in calculated particulate matter (PM) fields. Using the noise factors, an ensemble of 15 members is created. The range of modeled states of these ensemble members determines the model uncertainty. More details on the ensemble Kalman filter data assimilation system and its application to AOD are given in Bultjes et al. (2001), Koelemeijer et al. (2006b), and Timmermans et al. (2006).

4. The OSSE directed at aerosols

a. Creation of synthetic observations

Because the aim of this study is to evaluate the benefit of future observations that are not yet available, synthetic observations need to be obtained. The synthetic observations in this study are generated by performing a nature run with the LOTOS-EUROS model. The chosen study period from 15 July to 15 August 2003 covers the European 2003 heat wave. The period was chosen based on two criteria: it should contain a reasonable amount of cloud-free areas and periods and contain periods of elevated aerosol loadings. To approximate the resolution of the future satellite instrument, the nature run was performed at a horizontal resolution of 0.0625° latitude \times 0.125° longitude, approximately $7.5 \text{ km} \times 6 \text{ km}$. Because of the computational demands of the nature run with increased resolution, the model domain was limited to a quarter of its standard domain. The limited domain reaches from 42.5° to 60°N and -5°W to 30°E , covering the central part of Europe. The domain is chosen to cover some highly industrialized areas (Po Valley, Ruhr area, and

Poland) and regions where most ground-based measurements are available.

Although this study is limited to total AOD measurements, the OSSE system will be used in future experiments to determine the advantage of AOD profile measurements. One advantage of vertically resolved AOD measurements (e.g., from the A-band sounder; Siddans et al. 2007) might be the detection of elevated altitude aerosols such as desert dust. For this reason, a Saharan dust source was added during the second half of our study period (August 2003) by using a boundary condition for dust of $150 \mu\text{g m}^{-3}$ at the left half of the southern boundary of the model in layers three and four. The northward wind at the southern boundary during this period transports the dust over parts of the model domain.

From the nature run, both hourly synthetic ground-based measurements of PM_{2.5} (fine particles with a diameter $<2.5 \mu\text{m}$) have been created as well as synthetic spaceborne AOD measurements from a future satellite instrument, the FCI (see specifications in EUMETSAT 2006). The first is done by interpolation of the nature run values to 43 observation locations. The locations correspond to real stations, although it is stressed that in the study no real measurements from these stations are used. As can be seen in Fig. 1, most of the locations are concentrated in Germany and Austria, whereas there are no locations in, for example, France and Italy. The allocation of ground-based stations was performed to allow a differentiation of the results between areas with many and areas with few ground-based measurements.

The creation of hourly synthetic spaceborne AOD measurements was done in five layers by first computing AOD values from the concentrations fields of SO₄, NO₃, NH₄, dust, primary PM, black carbon, and sea salt from the nature run. For this computation, the approach from Kiehl and Briegleb (1993) is used. The five layers are 0–25, 25–500, 500–1500, 1500–3500, and 3500–5500 m. The AOD values in the top layer are determined by taking the concentrations of fields at the model top.

These AOD fields from the nature run represent the “true” state of the atmosphere; however, the AOD values as they would be measured in this situation by the FCI instrument are needed. Therefore, from the calculated AOD values by the model for the same five layers, satellite observations were retrieved corresponding to the FCI imager measuring total AOD column at $0.0625^\circ \times 0.125^\circ$ resolution. The retrievals are based on the optimal estimation method and are described in detail in Siddans et al. (2007). AODs are retrieved with accompanying error estimates that agree with instrument characteristics. The cloud information from the LOTOS-EUROS model input is used as a cloud mask in the procedure.



FIG. 1. Locations of simulated ground-based PM_{2.5} observations.

Figure 2 shows the total AOD calculated by the nature run and the corresponding synthetic total AOD data at 1200 LT on 20 July. For this time, a feature of the imager is visible. For low aerosol signals, the retrieved AOD from the imager stays closer to its a priori AOD, which is taken as the mean modeled aerosol over the whole domain and time period of the nature run.

b. Adaptations to model description

The synthetic measurements are subsequently assimilated into the assimilation model. For the assimilation, a LOTOS-EUROS version different from the version used for the nature run has been used. Using a nearly identical or similar model for both the nature run and the assimilation runs might lead to the identical twin problem: that is, the results from the nature run and subsequent experiments are too similar and not independent enough. The differences should ideally approximate the differences between results from a state-of-the-art model and the real atmosphere. Several adaptations of the model concerning emission factors, emission variability, and deposition characteristics have been tested for their ability to produce sufficiently large differences. The aim was to increase bias and root-mean-square error (RMSE) and decrease temporal correlation to values seen in model comparisons with ground-based measurements. From these tests, process descriptions (together with meteorology) showed to be a significant source for temporal variability (decrease in correlation). A combination of adaptations was applied. These adaptations

encompass a decrease in the horizontal resolution by a factor of 4, an emission reduction by daily changing factors combined with significantly lowered wet deposition and increased dry deposition. The decrease in horizontal resolution is also necessary to simulate the representativeness error between the observations and the model.

The differences between the PM_{2.5} concentrations from the nature and the assimilation model versions were analyzed for the full domain (see Fig. 3) and for 61 regularly distributed locations, in particular. The absolute differences and RMSE between both model versions are smaller than between real observations and model-simulated PM₁₀ (and most likely also PM_{2.5}) values (see, e.g., Vautard et al. 2007; Manders et al. 2009), because chemistry transport models systematically underpredict ambient PM₁₀ and PM_{2.5} concentrations. The underestimation is partly attributed to uncertainties in emissions estimates and missing sources and processes. The RMSE between the model versions used here is about half that of bias-corrected PM simulations in comparison to real observations (Manders et al. 2009), which are used in assimilation studies for PM₁₀ (Denby et al. 2008). It is expected that the differences between the models and observations will decline in the coming years because of improvement of the models and their input. So the (lower) RMSE between both model versions may correspond to model performance in 5–10 years time, when currently designed satellites are to be operational.

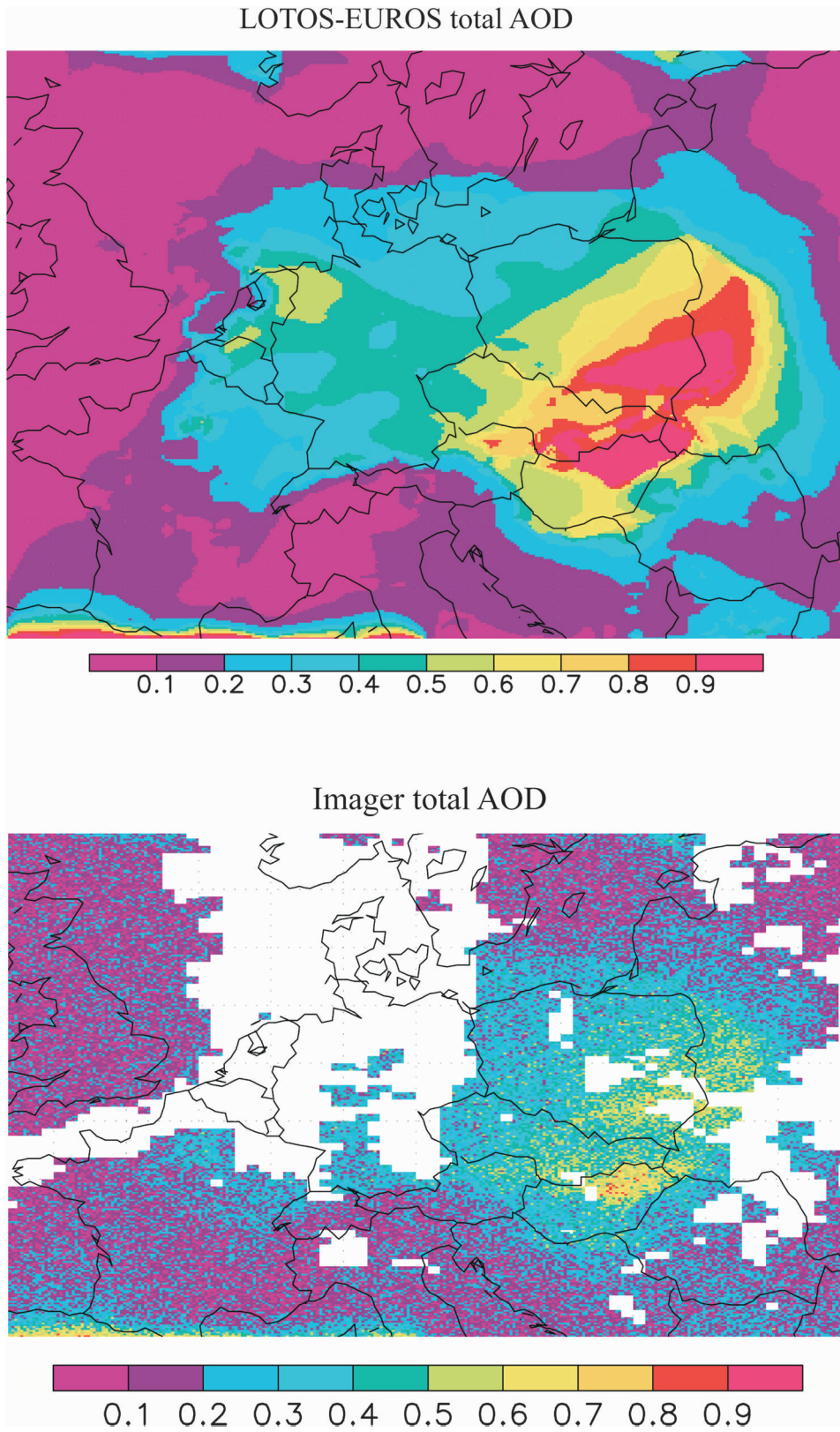


FIG. 2. Total AOD on at noon on 20 Jul (top) as calculated by the nature run using the LOTOS-EUROS model and (bottom) as determined for the FCI instrument.

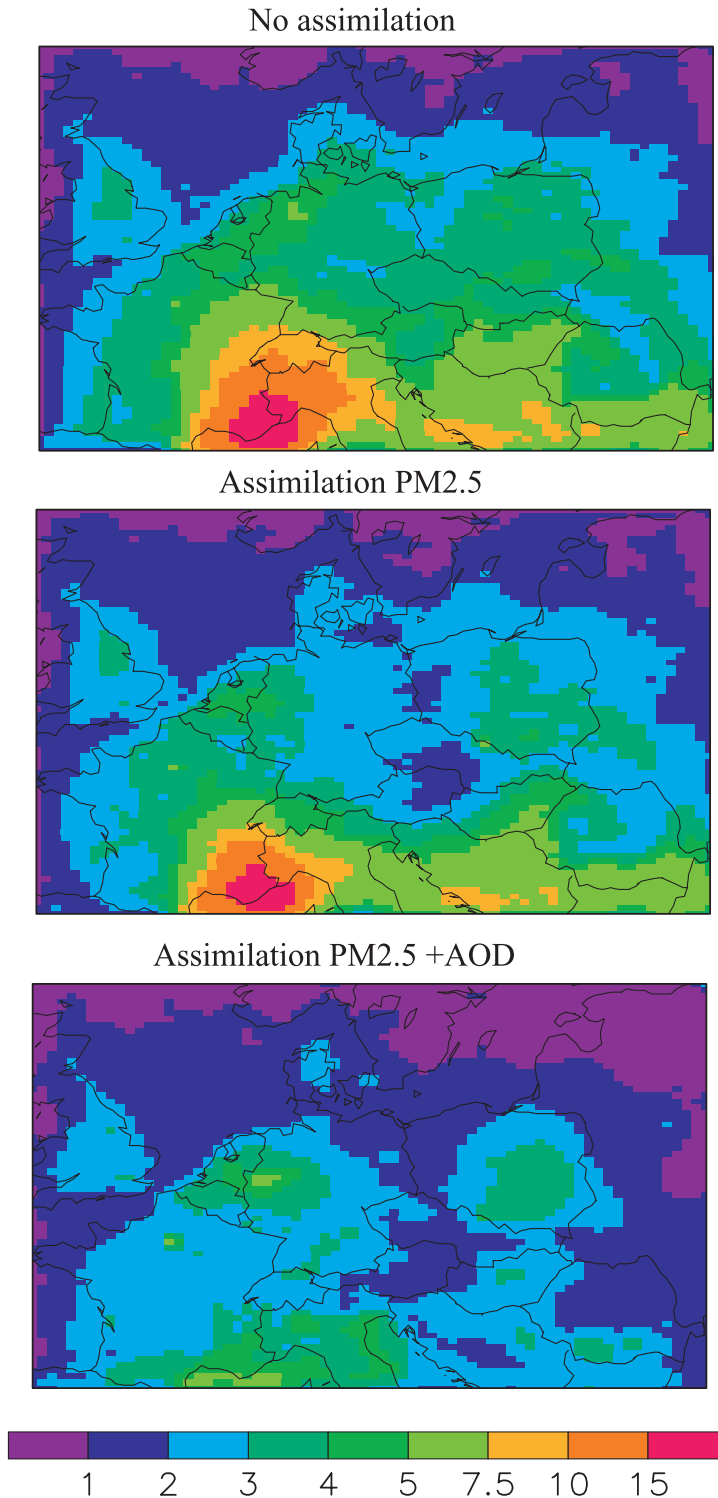


FIG. 3. RMSE ($\mu\text{g m}^{-3}$) compared to the nature run, averaged over 15 Jul–14 Aug 2003 for three different runs with the assimilation model: (top) without assimilation, (middle) with assimilation of hourly synthetic ground-based PM_{2.5} measurements, and (bottom) with assimilation of hourly synthetic ground-based PM_{2.5} measurements and hourly synthetic total AOD from FCI instrument. Note that no other measurement data than PM_{2.5} and AOD are assimilated in these experiments.

TABLE 1. Mean PM_{2.5} concentrations of the nature run and assimilation model run with and without assimilation of PM_{2.5} ($\mu\text{g m}^{-3}$) and AOD, RMSE ($\mu\text{g m}^{-3}$), and correlation between the assimilation runs and the nature run.

	Mean PM _{2.5} nature run	Mean PM _{2.5} assimilation run	Mean absolute difference	RMSE	Corr
No assimilation	9.2	11.0	1.8	4.8	0.78
Assimilation of ground-based PM _{2.5}	9.2	10.6	1.4	4.0	0.84
Assimilation of ground-based PM _{2.5} and imager AOD	9.2	9.3	0.1	2.9	0.88

c. Assimilation of synthetic measurements

With this adapted model version two assimilation experiments have been performed

- with assimilation of the synthetic hourly PM_{2.5} ground-level measurements only and
- with assimilation of the synthetic hourly PM_{2.5} ground-level measurements and the synthetic hourly AOD measurements from the imager.

Note that no other measurement data are assimilated in these experiments. In the assimilation process, noise factors were applied to the emissions of NO_x, SO_x, NH₃, and primary particles; the dry deposition velocity; and the boundary conditions of dust.

As usual in OSSEs, the results of the assimilation runs are compared to the nature run, which represents the true state of the atmosphere. Figure 3 shows the average RMSE between the different simulations and the nature run. Assimilation of only the synthetic ground-based PM_{2.5} measurements lowers the RMSE mainly over the region with many measurement locations (Germany, Austria, and the Czech Republic). The average reduction in RMSE at the 61 evaluation locations is 17% (see Table 1). Additional assimilation of the synthetic total AOD measurements from the imager further lowers the RMSE. As expected, the extra reduction of RMSE is mostly visible in the region without ground-based measurements and in regions where there is a large difference between the distorted run and the nature run. In this region (south of Europe), the RMSE decreases by a factor of 3, from an average value of about $9 \mu\text{g m}^{-3}$ to an average value of about $3 \mu\text{g m}^{-3}$. On the other hand, in regions with many PM measurements (e.g., Austria and the Czech Republic), some areas can be identified having an up to 20% lower RMSE. The results thus show a positive impact of adding AOD observations next to in situ observations.

5. Discussion and outlook

An OSSE system for aerosols has been set up that performs the assimilation of both ground-based PM_{2.5} observations, as well as satellite-based AOD measure-

ments in the chemistry transport model (CTM) LOTOS-EUROS. To our knowledge, this is the first OSSE application ever directed at aerosols. Although the approach presented here is in some respects very pragmatic, results clearly show the possibilities for evaluating the additional benefit of satellite measurements of AOD over in situ measurements of PM_{2.5}. A number of issues regarding OSSEs for aerosols are discussed and an outline of possible future experiments is presented.

Ideally, to avoid the identical twin problem, different models should be used for the nature run and the assimilations runs. In this study, an adapted model version is used for the generation of the synthetic observations. This is common practice in meteorological OSSEs. However, absolute concentration changes and changes in temporal variability are not easily introduced in a chemistry transport model without producing unrealistic results. Hence, by using the adapted model version, the identical twin problem is probably not completely avoided. For this reason, the results from this study should be used as an indication that the system is working, and the results should be interpreted in a qualitative sense. To avoid the identical twin problem, the use of two different models (with, e.g., different emissions, process descriptions, and/or meteorology) is recommended for future experiments.

The impact of the assimilated observations is affected by several factors. First of all, the accuracy of the observations relative to the uncertainty in the model determines to a large extent the influence of the observations on the analyzed fields. A large impact is advantageous for highly accurate observations but unfavorable when the quality of the observations is poor. It is therefore challenging but very important to use a realistic accuracy estimate in the assimilation of future observations.

Another factor that influences the extent of the data impact is the lateral boundary conditions in the regional CTM. When using fixed boundary conditions for the aerosol concentrations, the data assimilation system will not be able to introduce large changes close to the boundaries. In many situations the aerosol concentrations at the model boundaries are low and the influence on the data impact will be small. However, the influence is important when there is a large inflow of aerosol

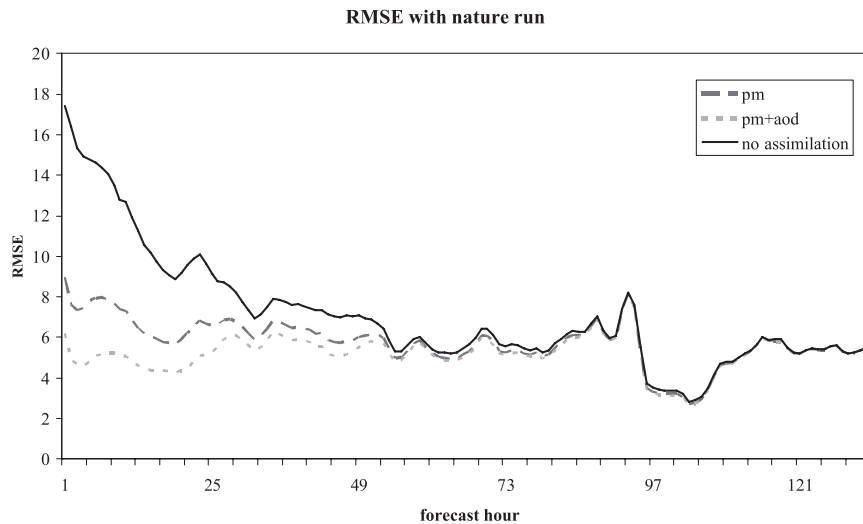


FIG. 4. RMSE ($\mu\text{g m}^{-3}$) with the nature run for the forecasts started on 25 Jul 2003. The runs are started from three different initialized fields corresponding to the assimilation model runs without assimilation (solid line), with assimilation of synthetic ground-based PM2.5 observations (long dashes), and with assimilation of both synthetic ground-based PM2.5 observations as synthetic satellite AOD observations (short dashes).

across the boundary. Such an inflow will not be captured in the model but will be present in the observations that are assimilated. To solve this problem it is possible to apply noise to the boundary conditions of the model in the assimilation, allowing the boundary concentrations to change. In this study noise was applied to the boundary conditions of dust. This was crucial because we have included a dust source at the southern boundary of the nature run to simulate the transport of desert dust into the model domain. The results show that this noise specification allowed the assimilation of the AOD observations to have a large impact close to the southern boundary.

A third important factor is the representativeness of the type of assimilated observations for the analyzed variable. In this experiment, the impact of integrated column AOD measurements from an imager instrument on analyzed and forecasted PM distribution is investigated. AOD is, however, a derivative quantity, and the link between PM and AOD depends on the composition, size, altitude, and concentration of the aerosols. Furthermore, the integrated column AOD observations do not provide any information on the altitude of the aerosols.

Several studies (Wang and Christopher 2003; Koelemeijer et al. 2006a) have shown that column AOD measurements in some cases show a good correlation with surface PM concentrations, whereas in other cases the correlation is poor: for example, in situations where high-level pollution is present influencing the total column AOD but not the surface PM concentrations. It is expected that in such cases, instruments providing

aerosol profile information will have a larger value for improving the surface PM distributions because they allow the discrimination of low-level pollution from high-level pollution from long-range transport (e.g., desert dust episodes or wild fires). Also, the use of aerosol observations from other space instruments, providing additional information on the observed aerosol, might be beneficial. The OSSE system developed here can and will be used to assess both the impact of different temporal resolutions, as well as a first-order impact of vertically resolved satellite observations of AOD. Furthermore, with some necessary adaptations, the OSSE system can form a useful tool for evaluation of other types of aerosol data from future satellite missions.

The aforementioned factors influence the analysis of air quality through the assimilation of observations. Concerning forecasting of air pollution using the analysis to provide initial conditions, a number of additional future challenges for air quality OSSEs can be identified. Forecasting air quality and atmospheric chemistry, in general, differs from the meteorological practice. Disturbances in a meteorological model will, in general, cause the runs to diverge from the nature run and lead to lower spatial correlation in time. Hence, in meteorological OSSEs, the performance of runs is often evaluated using the spatial correlation as a measure. Contrarily, chemistry transport models are stable systems because of the continuous input of emissions and the meteorology as driving forces. The tendency of the system to converge is illustrated with the results of two forecast simulations in Fig. 4. As found in previous studies on

ozone forecasts (Elbern et al. 2007; Blond and Vautard 2004), the forecasts using considerably different initial conditions have fully converged rapidly, after ~ 52 h. Inspection of all simulations shows that the system generally returns to the reference run in about two days. Because of this convergence the spatial correlation will not decrease in time, rendering the spatial correlation as a performance indicator meaningless. This highlights the need for a common framework, different from meteorological practice, to evaluate forecast experiments for air quality.

Another challenging aspect is the optimal design of a forecast experiment. At this moment, the full capability of the system is not used as the adjusted parameters (emissions, boundary conditions, and dry deposition velocity in this experiment) from the preceding assimilation in a forecast are not used. Given the influence of previous assimilation steps, stability of the system, and the lifetime of the aerosol, it is not known which window to use for this purpose; do we use the information from the last hour or the (weighted) average over the last two days? A similar reasoning applies to the forecast period. How long should the adjusted parameters be preferred over the long-term averages?

The stability of the model system raises another important issue. Given the short convergence time of the model system, a significantly higher temporal resolution than once every two days is needed to track the evolution of the aerosol distribution in time. On the other hand, aerosols have a lifetime of 1–2 days to a week, which is considerably longer than the hourly resolution of AOD data used in this experiment. Hence, it may well be that an AOD retrieval once every few hours in combination with in situ observations may be sufficient to track the aerosol distribution as well as an hourly AOD retrieval. This required temporal resolution is relevant, because it may impact the choice of satellite orbit (low polar versus geostationary).

Existing AOD observations from a geostationary satellite are available from the Spinning Enhanced Visible and Infrared Imager (SEVIRI; Wagner et al. 2007). The retrieval is currently limited to a daily value but retrieval of an AOD product at higher temporal resolution is foreseen. When these become available, the optimal temporal resolution can be addressed in a realistic setting, and the results from this study using synthetic measurements can be compared to results from the assimilation of the SEVIRI measurements.

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REFERENCES

- Blond, N., and R. Vautard, 2004: Three-dimensional ozone analyses and their use for short-term ozone forecasts. *J. Geophys. Res.*, **109**, D17303, doi:10.1029/2004JD004515.
- Brunekreef, B., and S. T. Holgate, 2002: Air pollution and health. *Lancet*, **360**, 1233–1242.
- Builtjes, P. J. H., H. M. ten Brink, G. de Leeuw, M. van Loon, C. Roblez Gonzalez, and M. Schaap, 2001: Aerosol air quality satellite data. BCRS USP-2 Rep. 00-33, 76 pp. [Available from Netherlands Remote Sensing Board Programme Bureau, Rijkswaterstaat Survey Department (BCRS), P.O. Box 5023, 2600 GA Delft, Netherlands.]
- Denby, B., M. Schaap, A. Segers, P. Builtjes, and J. Horalek, 2008: Comparison of two data assimilation methods for assessing PM₁₀ exceedances on the European scale. *Atmos. Environ.*, **42**, 7122–7134.
- Elbern, H., A. Strunk, H. Schmidt, and O. Talagrand, 2007: Emission rate and chemical state estimation by 4-dimensional variational inversion. *Atmos. Chem. Phys.*, **7**, 3749–3769.
- EUMETSAT, 2006: MTG mission requirements document. EUMETSAT Document EUM/MTG/SPE/06/0011 v2C, 146 pp. [Available online at http://www.eumetsat.int/idcplg?IdcService=GET_FILE&dDocName=PDF_MTG_MRD&RevisionSelectionMethod=LatestReleased.]
- Evensen, G., 1997: Advanced data assimilation for strongly nonlinear dynamics. *Mon. Wea. Rev.*, **125**, 1342–1354.
- Goede, A. P. H., 2005: CAPACITY user requirements document. KNMI Document UR 001 WP1000, 50 pp. [Available online at <http://www.knmi.nl/capacity/FinalDocs/user%20requirements.pdf>.]
- Kiehl, J. T., and B. P. Briegleb, 1993: The relative roles of sulphate aerosols and greenhouse gases in climate forcing. *Science*, **260**, 311–314.
- Koelemeijer, R. B. A., C. D. Homan, and J. Matthijssen, 2006a: Comparison of spatial and temporal variations of aerosol optical thickness and particulate matter in Europe. *Atmos. Environ.*, **40**, 5304–5315.
- , M. Schaap, R. M. A. Timmermans, C. D. Homan, J. Matthijssen, J. van de Kasstelee, and P. J. H. Builtjes, 2006b: Mapping aerosol concentrations and optical thickness over Europe—PARMA final report. MNP Rep. 555034001, 72 pp. [Available online at <http://www.rivm.nl/bibliotheek/rapporten/555034001.pdf>.]
- Lelieveld, J., 2003: Geostationary satellite observations for monitoring atmospheric composition and chemistry applications. EUMETSAT Final Rep. EUM/CO/02/1015/SAT, 64 pp. [Available online at http://www.eumetsat.int/idcplg?IdcService=GET_FILE&dDocName=PDF_MTG_REP01&RevisionSelectionMethod=LatestReleased.]
- Manders, A. M. M., M. Schaap, and R. Hoogerbrugge, 2009: Testing the capability of the chemistry transport model LOTOS-EUROS to forecast PM₁₀ levels in the Netherlands. *Atmos. Environ.*, **43**, 4050–4059.
- Masutani, M., and Coauthors, 2006: Observing system simulation experiments at NCEP. NOAA/NWS/NCEP Office Note 451, 34 pp.
- Robles González, C., M. Schaap, G. de Leeuw, P. J. H. Builtjes, and M. van Loon, 2003: Spatial variation of aerosol properties over

- Europe derived from satellite observations and comparison with model calculations. *Atmos. Chem. Phys.*, **3**, 521–533.
- Schaap, M., and Coauthors, 2004: Anthropogenic black carbon and fine aerosol distribution over Europe. *J. Geophys. Res.*, **109**, D18201, doi:10.1029/2003JD004330.
- , G. de Leeuw, B. Henzing, and P. J. H. Buitjes, 2006: Assimilation of aerosol optical depth over Europe in a regional chemistry transport model. *Proc. Seventh Int. Aerosol Conf.*, St. Paul, MN, American Association for Aerosol Research, 1839–1840.
- , R. M. A. Timmermans, M. Roemer, G. A. C. Boersen, P. J. H. Buitjes, F. J. Sauter, G. J. M. Velders, and J. P. Beck, 2008: The LOTOS-EUROS model: Description, validation and latest developments. *Int. J. Environ. Pollut.*, **32**, 270–290.
- Siddans, R., B. G. Latter, and B. J. Kerridge, 2007: Study to consolidate the UVS mission requirements for the oxygen A-band. EUMETSAT Rep. EUM/CO/05/1411/SAT, 265 pp. [Available online at http://www.eumetsat.int/idcplg?IdcService=GET_FILE&dDocName=PDF_MTG_REP31&RevisionSelectionMethod=LatestReleased.]
- Timmermans, R., M. Schaap, R. Koelemeijer, R. Schoemaker, G. de Leeuw, and P. Buitjes, 2006: Comparison between AATSR and MODIS AOD and assimilation in a regional chemistry transport model. *Proc. Fifth AT2 Workshop*, Crete, Greece, ACCENT, 44–46. [Available online at http://troposat.iup.uni-heidelberg.de/AT2/Reports_and_papers/2006_09_5th_wkshp_report_revised.pdf.]
- Vautard, R., and Coauthors, 2007: Evaluation and intercomparison of ozone and PM10 simulations by several chemistry transport models over four European cities within the CityDelta project. *Atmos. Environ.*, **41**, 173–188.
- Wagner, S., Y. M. Govaerts, A. Lattanzio, and Ph. Watts, 2007: Optimal estimation applied to the retrieval of aerosol load using MSG/SEVIRI observations. *Remote Sensing of Clouds and the Atmosphere XII*, A. Comerón et al., Eds., International Society for Optical Engineering (SPIE Proceedings, Vol. 6745), 67450A, doi:10.1117/12.737729.
- Wang, J., and S. A. Christopher, 2003: Intercomparison between satellite-derived aerosol optical thickness and PM_{2.5} mass: Implications for air quality studies. *Geophys. Res. Lett.*, **30**, 2095, doi:10.1029/2003GL018174.