**DNICast**

Direct Normal Irradiance Nowcasting Methods for Optimized Operation of Concentrating Solar Technologies

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Abstract
Small-scale dust outbreaks influence aerosol optical depth (AOD) locally. This is important for concentrating solar power plants (CSP) since aerosols strongly impact direct normal irradiance (DNI). CSP are often located in desert regions, thus close to dust sources where mineral dust outbreaks are likely to occur. Coarse resolution forecasting systems based on satellite observations or large-scale modelling may not be sufficient to capture those small-scale dust events.

In this study highly resolved modelling is performed with the chemical transport model EURopean Air pollution Dispersion-Inverse Model extension (EURAD-IM). This model includes sophisticated aerosol dynamics and aerosol chemistry schemes, and a variational data assimilation scheme. The system is embedded in the European Earth observation system MACC (Copernicus) and benefits from near-real time in situ and space borne measurements. This study investigates the performance of this model set-up to forecast AOD as a basis for DNI forecasts at CSP locations in southern Spain.

The EURAD-IM model is able to successfully represent local mineral dust events at the reference station Plataforma Solar Almeria (PSA). The effect of assimilating in-situ PM10 and PM2.5 measurements is limited, since data coverage is found to be sparse. Beyond the original project tasks, first results are presented with assimilated AOD information from MODIS satellite observations which help to improve the simulation of large-scale Saharan dust events.

Keywords: AOD, data assimilation, mineral dust, EURAD-IM, PM10, PM2.5
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1 Introduction

'Direct Normal Irradiance Nowcasting methods for optimized operation of concentrating solar technologies (DNICast)' is a project of the European Union's Seventh Framework Programme for research, technological development and demonstration framework. The goal of this project is to improve forecasts of Direct Normal Irradiance (DNI). These forecasts are needed for efficient operation of concentrating solar power plants (CSP) which have proven to be very efficient sources of clean power for the electrical grid.

Aerosols are especially important for DNI, since they can cause a reduction of DNI of up to 20% [e.g. Schroedter-Homscheidt et al., 2010]. Therefore, the aim of work package 2.2, 'Near-real-time aerosol monitoring and very-short-term forecasting', is to evaluate and improve state-of-the-art forecasting methods for aerosols as a prerequisite for radiation forecasts. Today, in most numerical weather prediction (NWP) models aerosol climatologies are used.

As a first step, existing aerosol forecast systems for aerosol optical depth (AOD) nowcasting applications are evaluated. In this study, we analyse the performance of the EUROpean Air pollution Dispersion-Inverse Model extension (EURAD-IM) model, which has been successfully used for air quality forecasting. Operational forecasts and analyses are run with EURAD-IM within the framework of various projects, e.g. MACC (now: Copernicus). Thus, the main interest of EURAD-IM applications has so far been to forecast concentrations of chemical species and particles.

In the DNICast project the assimilation-based model set-up similar to MACC was used to study the performance of the EURAD-IM model of forecasting the aerosol optical properties and densities. Three dimensional variational (3D-Var) data assimilation is performed using ground-based in-situ measurements of PM2.5 and PM10. New regional high-resolution nests were set up to focus on the region of CSP locations in southern Spain, in particular a 1km nest was place around the Plataforma Solar Almeria (PSA).

The focus in this project task is to investigate the aerosol forecasts in the vicinity of dust sources. Therefore, an assessment of a high resolution (few minutes time step, 1km grid) aerosol nowcasting scheme is made with EURAD-IM.

During the project it is revealed that hourly, ground-based measurements of particulate matter have been strongly reduced in Spain in the year 2013. In particular in the vicinity of solar power plant locations in southern Spain no measurements are available. Thus, beyond the project task, a new observation operator for the assimilation of AOD remote sensing observations has been developed for EURAD-IM. We present first assimilation results using MODIS AOD observations in this report. This specific project contribution will be further expanded in the future to find the best assimilation configuration for AOD forecasting in this region. The results will be published in a separate article.
2 Methods

2.1 EURAD-IM model description

EURAD-IM is an Eulerian meso-scale chemistry transport model involving advection, diffusion, chemical transformation, wet and dry deposition and sedimentation of tropospheric trace gases and aerosols [Hass et al., 1995; Memmesheimer et al., 2004]. It includes 3D-Var and 4D-Var chemical data assimilation [Elbern et al., 2007] and is able to run in nesting mode. As meteorological driver the Weather Research and Forecasting Model (WRF) is applied. EURAD-IM has been applied on several recent air pollution studies [Monteiro et al., 2013; Zyryanov et al., 2012; Monteiro et al., 2012; Elbern et al., 2011].

The modal aerosol dynamics model MADE [Ackermann et al., 1998] is used to provide information the aerosol size distribution and chemical composition. To solve for the concentrations of the secondary inorganic aerosol components, a FEOM (fully equivalent operational model) version, using the HDMR (high dimensional model representation) technique [Rabitz and Alis, 1999; Nieradzik, 2005], of an accurate mole fraction based thermodynamic model [Friese and Ebel, 2010] is used. The updated SORGAM module [Li et al., 2013] simulates secondary organic aerosol formation. The DREAM model [Nickovic et al., 2001] is implemented for surface mineral dust emissions.

2.2 Aerosol measurements

Ground-based in-situ PM10 and PM2.5 observations: AQ e-Reporting

Ground-based in-situ PM10 and PM2.5 observations are taken from the Air Quality e-Reporting (AQ e-Reporting) by the European Environment Agency (EEA) under Directives 2004/107/EC and 2008/50/EC. Measurement stations which provide hourly PM10 or PM2.5 observations are shown in Fig. 2.1. Please note that for measurements of year 2013, for the first time the reporting under Decision 97/101/EC (exchange of information (EoI) on ambient air quality) is no longer available. For the observations of interest in this study (hourly PM10 and PM2.5 observations at the Iberian Peninsula) this change resulted in an enormous reduction of reporting measurement stations compared to the years before. The in-situ PM10 and PM2.5 observations are used for 3D-var data assimilation in this study.

Ground-based remote sensing AOD observations: AERONET

The AERONET (AErosol RObotic NETwork) program provides ground-based remote sensing aerosol networks [Holben et al., 1998]. The program provides a long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases. The network imposes standardization of instruments, calibration, processing and distribution. The error estimate for the AOD AERONET AOD retrieval is 0.02. In this study, the AERONET observations are used for validation.

2 http://aeronet.gsfc.nasa.gov/
Figure 2.1: Locations of ground-based aerosol measurements on the Iberian Peninsula: In-situ PM10 and PM2.5 stations (yellow dots), and AERONET remote sensing measurement locations (violet dots). Locations of concentrating solar power (CSP) plants are indicated by black circles. The black polygon marks the region of the Level 2 nest (with 1km horizontal resolution).

Satellite-based remote sensing AOD observations: MODIS

The MODIS Aerosol Product monitors the ambient aerosol optical thickness over the oceans globally and over a portion of the continents [Levy et al., 2013]. Daily Level 2 data are produced at the spatial resolution of a 10x10 1-km (at nadir)-pixel array. There are two different retrieval techniques for AOD over land and AOD over ocean. The error estimate is 0.03+(0.05 _AOD) for AOD over ocean and 0.05 + (0.15 _ AOD) for AOD over land [Levy et al., 2015a, b].

3 http://modis-atmos.gsfc.nasa.gov/MOD04_L2/
2.3 Model set-up

A nested grid structure was used for the meteorological model WRF and the chemistry transport model EURAD-IM in this simulation (Fig. 2.2). The coarse domain with 15km horizontal resolution covers western Europe. The first nest has a resolution of 5km and is located over the Iberian Peninsula. The second nest with the _nest grid (1km horizontal resolution) is placed around Plataforma Solar Almeria (PSA). The timesteps for the three grids are 30, 20, 10 seconds for WRF and 300, 120, 30 seconds for EURAD-IM.

The assimilation set-up is similar to the one that is applied within the MACC/Copernicus\textsuperscript{4} project with EURAD-IM [Marécal et al., 2015]. 3D-Var data assimilation is performed using hourly in-situ PM10 and PM2.5 observations. Additional runs beyond the project tasks were performed using MODIS AOD observations. The assimilation is done hourly using all available measurements that are available within the time frame of +/- 15 min before and after the assimilation time.

In accordance with other work packages within DNICast, the simulation is run for the time period March - May 2013.

\textsuperscript{4} http://www.gmes-atmosphere.eu/
3 Results

3.1 Analysis increments

Figure 3.1 shows a typical example of AOD distributions from the forecast, the analysis based on ground-based in-situ PM measurements, and the analysis based on MODIS satellite AOD measurements. The plots show the modelled AOD for 22nd May, 2013, 13:00UTC for the three different simulation configurations and the corresponding MODIS retrieval.

The forecast and the analysis based on ground-based PM measurements show a very similar pattern (top panels of Fig. 3.1). The analysis increments display small patches of higher AOD, as compared to the forecast, e.g. in northern Portugal and Murcia. This pattern is a typical feature in the model: the model tends to underestimate surface concentrations of particles, thus assimilation increments are more often positive than negative. The effect on the total column AOD is limited since ground-based in-situ measurements only provide information about surface layer concentrations.

The bottom left panel of Fig. 3.1 shows the analysis result from the assimilation of MODIS measurements. When assimilating MODIS satellite measurements, the influence on AOD is larger than in the analysis based on in-situ PM measurements. The size of the analysis increments of the satellite measurements are larger compared to the in-situ particle measurements, and the absolute values of the differences are higher. Schwartz et al. [2012] get similar results comparing the analysis increments from remote sensing and in-situ observations. The available MODIS measurements are displayed on the bottom right panel of the same figure. Here, some characteristics of the MODIS retrieval are visible: Different retrieval algorithms are applied over land and over sea. The retrieval algorithm over sea is usually more stable than the one over land, such that in many cases more AOD information is available over the ocean. Over land, the retrieval algorithm fails in case of high AOD values and high surface reflectance. In the example presented here, this effect is visible in southern Spain and central Portugal.

3.2 AOD timeseries at AERONET stations

This section presents AOD timeseries for three different AERONET locations in central and southern Spain. The AERONET measurements shown here were not assimilated, such that they can be used for validating the simulation results. The main focus of this work concentrates on the station at Plataforma Solar Almeria (PSA) which serves as a reference station (supersite) in this project. Additional simulations from the 1km domain are available at PSA.

Plataforma Solar Almeria

Figure 3.2 shows timeseries of AOD at PSA for different model runs in the 5km domain. Since no ground-based measurements are available in the surroundings of Almeria (Fig. 2.1, Sect. 2.2) the forecast without data assimilation is similar to the analysis based on ground-based measurements. In general, the modelled AOD from the forecast run is in good agreement
with the observations except for some Saharan mineral dust events. During the simulated period of three months several

Figure 3.1: AOD distribution at 22nd May, 2013, 13:00UTC for different simulation configurations: forecast without data assimilation (top left panel), analysis based on EEA ground-based PM10 and PM2.5 observations (top right panel), and analysis based on MODIS satellite measurements (bottom left panel). Additionally, MODIS AOD measurements for the same time are shown (bottom right panel).
Figure 3.2: Timeseries of AOD at Plataforma Solar Almeria (PSA) for three different simulations in the 5km domain for March-May 2013: forecast without data assimilation (solid black line), analysis using in-situ PM10 and PM2.5 measurements (solid blue line), analysis using MODIS observations (dashed blue line). AERONET measurements are plotted in red for validation.

Events with high AOD (above 0.2) are identified. During the event in the last week of April, the modelled AOD is in good agreement with the AERONET measurements. In some cases when the EURAD-IM model simulates high AOD, no valid measurements are given, e.g. at 16th March and 25th April. High AOD values during Saharan dust events are represented within the MODIS analysis whenever MODIS observations are available. The analysis using MODIS measurements shows improved, higher AOD values than the forecast at 21st March, 15th April, 4th, 22nd, 24th, and 26th May. At other days, no valid MODIS measurements are available, e.g. at 25th and 27th May. The main sources of Saharan dust are located outside the model domain. Thus, Saharan dust in the simulation is primarily caused by boundary conditions from the global ECMWF model and sedimentation and not by mineral dust emissions inside the model domain. Local mineral dust events are discussed in Section 3.3.
Figure 3.3: Timeseries of AOD at Plataforma Solar Almeria (PSA) for March 2013 in two different model domains: nest 1 with 5km horizontal resolution (solid lines), nest 2 with 1km horizontal resolution (dashed lines). The top panel displays forecast results without data assimilation, the bottom panel shows 3D-Var assimilation results using MODIS observations. AERONET measurements are plotted in red for validation.

Comparison of model results from the 5km and 1km domains

This section compares the AOD results of the 5km domain with the results of the 1km domain at the location of PSA. The results of the forward run without data assimilation are shown in the top panel of Fig. 3.3. The largest absolute differences are approximately 0.05 AOD. No clear advantage of either grid is visible here, hence the 5km simulation is too high on the 7th March, while the overestimation of AOD is higher in the 1km forecast then in the 5km forecast on the 13th March. Apart from these few exceptions the differences between the 1km domain and the 5km domain are small (below 0.02 AOD).

The bottom panel of Fig. 3.3 shows a comparison of the corresponding 3D-Var analysis results with MODIS observations assimilated. It should be noted that MODIS footprints are larger than 1km² so that the advantage of the 1km grid can not be used for the location of observation. The correlation length at the ground is set to 5km for both model domains. In the 1km grid analysis peaks of high AOD values are present at the times of available MODIS data. Here, the 5km grid simulation is in better agreement with the AERONET observations. However, this result should be handled with care, since the MODIS AOD retrieval is systematically higher than the AERONET retrieval in the analysed time period. Additionally, the high error of the MODIS AOD retrieval over land is in the order of magnitude of the observed value.
To conclude, in this specific set-up for the given application (AOD forecasts for CSP location in southern Spain), the 1km domain has no advantage compared to the 5km domain. There is no ground station data available, for which use of a finer grid would be favourable. The larger 5km domain also benefits from observations which are located outside the 1km domain. However, these conclusions are only valid in this special set-up concentrating on the optical properties of aerosols. High resolution forecasts are valuable, e.g. for AQ simulations of surface layer particles with available ground observations.

Further AERONET locations

AOD timeseries for the AERONET station in Madrid are shown in Fig. 3.4 in central Spain far away from the coast. One reason for the selection of the station in Madrid was its location close to a ground-based measurement station of PM10 and PM2.5. In most cases the simulation results are able to represent the AOD measurements well. Despite the in-situ measurement station in the vicinity, in most cases there are only small differences in AOD visible between the forecast without data assimilation and the analysis based on in-situ particle measurements. But there are also some situations in which the ground based measurements are valuable, e.g. during the last days of May when the analysis with EEA observations improves the AOD forecast. The assimilation of MODIS satellite measurements corrects the overestimation of AOD at 4th May and the underestimation at 13th May.

Figure 3.5 shows timeseries plots of AOD for the AERONET station Badajoz close to some CSP locations at the Portuguese border. The distance to the next EEA measurement station is about 50 km. In March and the first half of April, the number of valid observations is limited for this station. The AOD timeseries show similar characteristics as observed at the other locations. The forecast without data assimilation is mostly similar to the analysis based on EEA measurements. AOD is underestimated by the model during Saharan dust events at the end of April and May. The analysis including MODIS measurements can improve the AOD forecast, e.g. at the 13th May, but valid retrieval results are only infrequently available for this location.
Figure 3.4: AOD timeseries at Madrid for March-May 2013. Colours as in Fig 3.2.
3.3 Local mineral dust events in Almeria

This study focusses on local mineral dust events, since the high resolution modelling using EURADIM is designed to be a suitable tool to capture these events which are problematic for coarse resolution forecasting systems. In-situ measurements would have been of great value for this task. However, as they are not present in the region around PSA, the forecast without data assimilation will be discussed. Five local mineral dust events are identified at the AERONET station Plataforma Solar de Almeria (PSA) in the investigated time period (March-May 2013). The dates of these dust outbreaks are the 11th, 20th, and 22nd March, the 25th April, and the 15th May. High concentrations of mineral dust in the surface layer of the model cause a local increase of AOD values of 0.1 in comparison with the surrounding area. Therewith, the values of AOD at PSA are 0.1 during the events in March and May, and 0.4 during the dust outbreak in April. The simulation results are in good agreement with the AERONET AOD observations during the local dust events (see Fig. 3.2), thus in case of Almeria, the EURAD-IM model is able to simulate these events in a realistic way.

Figure 3.6 shows the modelled AOD around Almeria in the 5km and 1km domain during the local dust event at 11th March, 16 UTC. The forecast results from the 5km and 1km domains
show a similar AOD pattern. The maximum values of AOD are slightly higher in small-scale structures in the 1km simulation. At this time, no MODIS measurements were available. Thus the result from the analysis run looks similar (not shown). The corresponding concentration of mineral dust at the surface layer exceeds 240, as shown in Fig. 3.7.

Figure 3.8 shows the AOD at 25th April at 17 UTC in the 5km domain. Here, high AOD values are observed over Spain. The highest AOD values are present in the south-eastern part of Spain. Here, a local mineral dust plume reaches out from Murcia southwards to Almeria and contributes to the highest AOD values in the model domain.

Figure 3.6: AOD at 11th March, 2013, 16:00 UTC around PSA from the EURAD-IM forecast from the 5km (left panel) and 1km domain (right panel).
Figure 3.7: Mineral dust at surface layer 11th March, 2013 from the forward run in the 5km domain.
Figure 3.8: AOD at 25th April, 2013 in the 5km domain for three different simulation configurations: forecast without data assimilation (top left panel), analysis based on EEA ground-based PM10 and PM2.5 observations (top right panel), and analysis based on MODIS satellite measurements (bottom left panel). Additionally, mineral dust at surface layer from the forecast without data assimilation is shown (bottom right panel).
4 Conclusions

This study investigates the potential of EURAD-IM with assimilated in-situ PM measurements to estimate the aerosol optical properties in the situation of local mineral dust events. Therefore, a simulation period of three months is analysed at the location of PSA in southern Spain. Whereas Saharan dust (with source terms outside the model domain) is often underestimated nearby, local dust events are found to be well represented at this location. The EURAD-IM is able to capture these small, localised events that increase AOD values up to 0.1. The impact of those events is smaller than large Saharan dust events, but can not be neglected. Surface layer dust events do not only influence AOD, but also contribute to soiling on the reflectors of concentrating solar power plants.

During this study it revealed is that the measurement basis for aerosols is problematic in the arid regions of southern Spain. First, no hourly in-situ PM10 and PM2.5 measurements are provided around the CSP locations in southern Spain. MODIS AOD retrievals over land often fail in the regions of high surface reflectance and in situations of high aerosol load. In addition, the MODIS AOD observation show a positive bias compared to AERONET.

In the future, assimilation experiments will be continued to find an optimized set-up to make best use of the sparse existing aerosol observations. Long-term statistics will be investigated by analysing the results in the operational forecast system with EURAD-IM.
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