Answer to Referee 1

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Dear Referee 1,

we thank you for your comments on our manuscript. Below we present our answers to your comments (italics) accompanied by the changes we performed in the manuscript (blue color).

On behalf of the authors

Daniel Rieger

1) The fact to explicitely diagnose mineral dust emissions and transport is not new, but it seems this was not the case in the German weather forecast model. This is thus a large improvement even if it is not a new scientific research. Many models are calculating all aerosols able to modify the radiation properties, including in forecast, as, for example, for the COPERNICUS CAMS daily forecast. Please improve the bibliography about forecast in Europe. For analysis or regional forecast, some of them are already online to account for the direct and indirect effects of aerosols (see papers by A.Baklanov in ACP, among others).

A literature review on dust forecasts and impacts on solar power production has been included in the paper:

Driven by the growth of renewable energy shares in electricity production, the accuracy of solar NWP and power forecasts has to meet increasing standards. Thus, also the literature in this field of application is growing, even if still being a young area of research.

Current operational NWP models are unable to account for the effect of mineral dust during such episodes as they are relying on aerosol climatologies. Nikitidou et al. (2014) investigated the spatial and temporal variability of aerosols over Europe and stress the necessity for near real-time forecasts of aerosol loads instead of climatological values. In areas of high desert-dust intrusions or intense anthropogenic activities, the reduction of direct normal irradiance (DNI) was found to reach values of up to 35 % and 45 %, corresponding to 4 and 6 $\mathrm{kW\,h\,m^{-2}}$ per day. Recently, Casado-Rubio et al. (2017) showed that considering prognostic dust aerosol considerably improves DNI forecasts in Spain and the Canary Islands which is of great importance for concentrating solar power (CSP). These findings are supported by the study of Schroedter-Homscheidt et al. (2016) who apply an interactive aerosol scheme for clear sky cases. Gleeson et al. (2016) highlight the importance of using accurate aerosol concentration, optical properties and an accurate vertical distribution of aerosols in NWP forecasts of shortwave radiative fluxes in case of a wildfire. Concerning mineral dust, Bangert et al. (2012) have shown a significant potential to improve the surface temperature forecasts during a strong Saharan dust event over southern Germany if dust as well as direct and indirect effects are considered in the NWP system COSMO-ART (COnsortium for Small-scale MOdeling - Aerosol and Reactive Trace gases).

Since recent research has shown the importance of meteorology and aerosol or chemistry feedback in many research areas, many online coupled mesoscale meteorology atmospheric chemistry models have been developed. Baklanov et al. (2014) gives an extensive overview of such models in Europe. Considering prognostic aerosols and the interactions with the atmosphere in NWP models is costly in terms of computing time. However, thanks to the increase in computer power, there are several modelling systems worldwide providing daily forecasts of mineral dust distributions. Table 1 provides an overview on current operational mineral dust forecasting models. A more detailed description of available daily mineral dust forecasts and activities in this research area can be found at the World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) (2017).

Table 1. Overview on operational mineral dust forecasting models.

Model name	Institution	References
BSC-DREAM8b	Barcelona Supercomputing Center	Pérez et al. (2006); Basart et al. (2012)
NMMB/BSC-Dust	Barcelona Supercomputing Center	Pérez et al. (2011); Haustein et al. (2012)
DREAM8-NMME-MACC	South East European Virtual Climate Change Center	Nickovic et al. (2001); Pérez et al. (2006)
LOTOS-EUROS	The Netherlands Organisation for Applied Scientific Research	Manders-Groot et al. (2016); Manders et al. (2017)
SKIRON	University of Athens	Spyrou et al. (2010)
CAMS	European Centre for Medium-Range Weather Forecasts	Morcrette et al. (2009); Benedetti et al. (2009)
Met Office UM	UK Met Office	Woodward (2001, 2011)
NGAC	National Centers for Environmental Prediction	Lu et al. (2016)
GEOS-5	National Aeronautics and Space Administration	Nowottnick et al. (2011)

A quantitative example of solar energy reduction due to mineral dust is given by Calinoiu et al. (2013). For 5 dust episodes in Romania, a reduction in collectable PV power of 6.5 % to 17.5 % was reported. Perry and Troccoli (2015) investigated a controlled fire burn in Canberra, Australia, and indicated an overall PV power reduction of 7 % during the study period and a peak reduction of 27 %. Besides a more accurate radiation forecast, operational dust forecasts also provide the possibility to account for the deposition of dust on PV panels and for better maintenance planning. For a review on energy yield losses by dust deposition see Sayyah et al. (2014).

Within this paper, the focus is on the beginning of April 2014, when Central Europe was influenced by an intensive Saharan dust outbreak.

2) This model improvement is applied for a specific application, the photovoltaic power production. This aspect is more new and more related to the ACP topics. The study present two different topic: the improvement of the model and the impact of the improved mineral dust calculations on PV production. But there is no validation of the improved model, on the specific test case (only one day). However, many measurements exist and could give a larger confidence on the quantification of the impact.

We focus on 4 April 2016 and provide some measures for 3 April and 5 April 2016 as well in table 5 for the reason, that this was one of the most severe Saharan dust events with respect to the economic loss for the PV power sector. A disadvantage of focusing on this episode is that most of the time the target region is covered by clouds. Hence, only very few remote sensing measurements for very short time ranges are available. We now included measurements where available and appropriate as you will see in the answers to question 6.

We agree that a much larger time range is necessary to validate the mineral dust forecasts. For this reason, daily mineral dust forecasts are performed as part of the PerduS project since October 2016. The results of these forecasts are continuously validated during Saharan dust outbreaks. The results so far are promising and it is planned to publish an in-depth validation of the mineral dust forecasts at a later stage of the PerduS project.

3) The section 2 is very complete about the model description. Many details are provided, but, if this is not new for this paper, some references would be enough.

The mineral dust emission scheme and the aerosol-cloud interaction that are incorporated into ICON-ART are not described consistently in another publication so far. We think that the details we provide in section 2 are absolutely necessary for the readers to have access to the underlying equations and methods. From our own experience, we know how frustrating it can be to search for this information distributed amongst several publications and sometimes even grey literature.

4) 2.2 Radiation: We agree that the complex refractive index is probably one of the sensitivie parameter for this kind of study. Please provide more precisely the values used (a figure for example). Did you already made sensitivity tests to have the range of uncertainty of your results?

We have conducted a literature review in order to put the refractive indices used into perspective. The studies used are shown in Tab. 2 and the values for the real part of the refractive index in Fig. 1 and for the imaginary part in Fig. 2. The specific studies and the influence of the mineralogical composition of the mineral dust are discussed in detail in Gasch (2016, pp. 55), Stanelle (2008) and Stanelle et al. (2010). Due to this existing discussion and as our values of the refractive index are the same ones as used for COSMO-ART we would like to limit the discussion in this publication.

It is beyond the scope of our study to investigate the uncertainties in our results due to the radiative properties of mineral dust, as many factors can contribute.

First, the usage of Mie calculations assumes sphericity for the mineral dust particles, an assumption which is generally not fulfilled for single particles, but introduces negligible errors for flux related quantities and albedo (Mishchenko et al., 1995, 1997). Second, the mineralogical composition of the dust is assumed to be spatially homogeneous, an assumption which is generally also not fulfilled (Petzold et al., 2009) and presents a great uncertainty in mineral dust radiative forcing (Myhre and Stordal, 2001). A problem prevents a more detailed description for our study: The variation in the refractive index within source regions can be considerable (Petzold et al., 2009) and we are not aware of spatially highly resolved observations from our source region. Third, the optical properties of mineral dust can change during transport, e.g. due to transport processes or coating with other materials, a mechanism which is not included in ICON-ART so far. Nevertheless, we can achieve a good representation of the mineral dust radiative properties, as the influence of differences in the refractive indices is small compared to the influence of a varying size distribution (Myhre and Stordal, 2001). The latter effect is represented in ICON-ART due to the newly implemented size-dependent parametrization of the optical properties.

In order to validate the above statement, we conducted Mie calculations for the refractive indices differing most from ours (Fig. 3), namely that of Volz (1972) and Köpke et al. (1997) , as well as for varying median diameters (Fig. 4). The results clearly show that changes in the size distribution lead to a stronger signal than changes in the refractive index. The effect of the size-dependent parametrization of optical properties is discussed in more detail in Gasch (2016, p. 94).

Please note, that as part of the review process in Gasch et al. (2017) we have added a more detailed discussion on the assumption of spatially homogeneous mineral dust mineralogical composition there.

In summary, as the change of the mineral dust radiative properties can be caused by various processes, we think that further research is necessary before the uncertainties of the results can be answered quantitatively. A better description of the radiative properties of mineral dust can yield further improvements of the impact on photovoltaic power generation.

Table 2. Overview of studies determining mineral dust refractive indices.

Publication	Characterisation	Source	Collection	Waveband	Acronym
Petzold et al. (2009)	SAMUM	Sahara	Aircraft	SW	SAM
Helmert et al. (2007)	Compilation	Various	-	SW, LW	HEL
Fouquart et al. (1987)	ECLATS	Sahara	Niamey, Niger	LW	FOU
Köpke et al. (1997)	GOADS Comp.	Various	-	SW, LW	KOE
Volz (1973)		Sahara	Barbados	LW	SVO
Volz (1972)	Rain-out Dust	Various	USA	SW, LW	DVO
Dubovik et al. (2002)	AERONET	Various	Worldwide	SW	DUB

5) 4 Model setup: the two possible ways are explained: 1. Compare the NWP with the climatology and the really resolved dust emissions. 2. Use only the really resolved model to quantify the impact of dust on PV production, The authors stated that only the 2nd approach is useful for their study. Why not the two? The approach 1 will provide the benefit to have a better *methodology for dust and to quantify the confidence is the future results about PV. The 2 will provide the impact on PV. The two are complementary.*

As proposed, we repeated our case study using the outlined approach 1. Therefore, a setup was chosen that mimics the operational system as close as possible. In this case, which is titled FF_{clim}, the bulk-microphysics scheme (Doms et al., 2011; Seifert, 2006) together with the accompanying calculation of the ice effective radii used in operational NWP and the aerosol climatology by Tegen et al. (1997) are used. The corresponding results are given in the following.

The first row in Figure 5 is identical to Figure 6 in the paper. It shows the horizontal distribution of SIS for the simulations TT and FF, and for the satellite product SARAH-2 at 4 April 2014, 12:30 UTC. In addition, the horizontal distribution of SIS for the simulation FF_{clim} is plotted in the second row. Figure 6 (cf. Figure 9 in the paper) shows the results of forecasted SIS and normalized PV power at four locations for the FF_{clim}, FF and TT cases in comparison to surface observations. Additionally, Table 3 (cf. Table 5 in the paper) gives the statistical measures for all 26 pyranometer stations. A clear improvement with respect to the default setup FF_{clim} can be observed in all three evaluations. The partially large differences between the FF_{clim} and the FF or TT case are the cumulative result of the described changes in the setup (bulk-microphysics, ice effective radii, aerosol climatology) and would not allow to quantify the improvement due to prognostic mineral dust and dust atmosphere interactions. Thus, we decided to present this additional evaluation in the answer to the reviewer only.

6+7) Specifically, because there is no real validation of the test case with measurements in the paper. Before to quantify the impact of dust on PV, it is necessary to prove that your simulation has correct order of magnitude and variability of AOD and surface PM2.5 and PM10. A lot of measurements exist in Europe and could be used for that (AERONET, EMEP).

5.1 Simulated mineral dust distribution: The Figure 6 (originally 5) presents comparisons between the model and measurements. It is necessary to done the same with the Figure 4 for AOD, by using AERONET stations for example. If you consider there is no enough stations in your nested domain, you can present, at least, a comparison with the largest one. As you are studying only one day, this would be also interesting to see model validation for the days before, in order to better understand if the mineral dust plume is well transported or not.

We thank the reviewer for the suggestion to add additional comparisons with measurements to our paper. We decided to include a comparison with AERONET stations. Additionally, we outline our evaluation strategy in the following:

For evaluating our modelling results we have thoroughly explored different types of available measurements. As a first step, we qualitatively compared our results to satellite, ceilometer, lidar and AERONET observations. The spatial distribution and temporal evolution of mineral dust as simulated over Europe is in good agreement with the available measurements. Unfortunately, these observations of mineral dust are hampered by the presence of clouds. The areas with high mineral dust loads coincide also with cloudy conditions and only few observation time steps within the period of interest are available for a quantitative comparisons. Nevertheless, in Figure 7 and Figure 8 we show mineral dust aerosol optical depth (AOD) as forecasted by with 20 km grid spacing in case TT and on top of that AERONET observations in filled circles (Figure 8 only due to the number of available measurements in the domain). The observations are averaged within a time interval of 1

Table 3. Statistical measures describing the quality of the simulated PV power values using data of all 26 pyranometer stations for different lead times. Values are given for the root mean square error (RMSE), the mean absolute error (MAE), the bias (BIAS), the standard deviation of errors (STD) as well as the minimum and maximum error (E_{min}, E_{max}) in W m^{-2}. Bold values mark the better simulation.

20140403 (lead time 0-23h)						
	RMSE	MAE	BIAS	STD	E_{min}	E_{max}
FF_{clim}	0.113	0.053	0.041	0.106	**-0.336**	0.603
FF	0.099	0.049	0.013	0.099	-0.534	**0.554**
TT	**0.092**	**0.044**	**0.006**	**0 092**	-0.542	0.563
20140404 (lead time 24-47h)						
	RMSE	MAE	BIAS	STD	E_{min}	E_{max}
FF_{clim}	0.152	0.079	0.057	0.141	**-0.605**	0.568
FF	0.124	0.059	0.009	0.123	-0.660	0.546
TT	**0.103**	**0.048**	**-0.004**	**0.103**	-0.672	**0.442**
20140405 (lead time 48-72h)						
	RMSE	MAE	BIAS	STD	E_{min}	E_{max}
FF_{clim}	0.156	0.082	0.067	0.141	-0.437	0.629
FF	0.110	0.054	0.029	0.106	**-0.405**	0.577
TT	**0.079**	**0.040**	**0.003**	**0.079**	-0.418	**0.418**
20140403-20140405 (lead time 0-72h)						
	RMSE	MAE	BIAS	STD	E_{min}	E_{max}
FF_{clim}	0.141	0.071	0.055	0.130	**-0.605**	0.629
FF	0.111	0.054	0.017	0.110	-0.660	0.577
TT	**0.092**	**0.044**	**0.001**	**0.092**	-0.672	**0.563**

hour before target time and represent level 2 coarse mode AOD at 500 nm (derived with Direct Sun Algorithm (DSA) Version 2, see also https://aeronet.gsfc.nasa.gov/version2_table.pdf and Spectral Deconvolution Algorithm (SDA) Version 4.1, see https://aeronet.gsfc.nasa.gov/new_web/PDF/tauf_tauc_technical_memo.pdf). The arrival of the dust cloud in eastern Germany is observed by the station Lindenberg. There is only a small spatial discrepancy with the forecasted location of the dust cloud. Note, that the region with rapid increase of mineral dust concentration also visualizes the weak frontal zone spanning from the North Sea over eastern Germany to the south-east of Europe (cf. section 3 in the paper). The magnitude of predicted AOD values in the closer surrounding match the observation well. The arrival of the dust cloud in Hohenpeissenberg (south Germany) is observed on the preceding day. The arrival is a little bit too late, but the temporal increase in dust load seems to be captured very well (not shown as only 14 observation points are available). The disadvantage and reason, why we did not evaluate against ground based PM2.5 and PM10 measurements is that they are not able to give a selective information about the mineral dust concentration. And for high-mountain stations, which may be less influenced by local emissions, there is in general a big difference between real and model altitude.

For the paper however we decided to show ground based observations of radiation due to their many advantages: dense spatial coverage, high temporal resolution, approved data quality. Ground based radiation measurements and related observation difficulties and influences are also best comparable with those of PV panels, where our objective is laid on. We also explained why satellite observations have to be treated with caution (see section 5.2). Not shown in the paper are evaluations against SYNOP observations of other meteorological parameters as they did not provide additional insight. As the reviewer proposed, we now included also the above mentioned comparison with AERONET stations in the paper in section 5.1:

A qualitative comparison to satellite, ceilometer and lidar observations shows that the spatial distribution and temporal evolution of mineral dust as simulated over Europe is in good agreement with the available measurements. Unfortunately, these observations of mineral dust are hampered by the presence of clouds. The areas with high mineral dust loads coincide also with cloudy conditions and only few observation time steps within the period of interest are available for a quantitative comparisons. In Figure 5 the mineral dust aerosol optical depth as forecasted at 20 km grid spacing for case TT is shown for 4 April 2014. On top of that, filled circles provide the corresponding AERONET measurements. The observations are averaged within a time interval of 1 hour before target time and represent level 2 coarse mode AOD at 500 nm (derived with Direct Sun Algorithm (DSA) Version 2 and Spectral Deconvolution Algorithm (SDA) Version 4.1). The arrival of the dust cloud in eastern Germany is observed by the station Lindenberg. There is only a small spatial discrepancy with the forecasted location of the dust cloud. Note, that the region with rapid increase of mineral dust concentration also visualizes the weak frontal zone spanning from the North Sea over eastern Germany to the south-east of Europe (cf. section 3).

8) What about local resuspension? The problem with mineral dust is not only the plume above the PV unit but also the deposition. The deposition is not only dry or wet, but there is also mainly very local emissions, due to resuspension and directly on the PV units.

For local resuspension of mineral dust we would have to account for the deposited amount. The availability of dust for resuspension out of this reservoir most likely also has to be parameterized with respect to the prevailing meteorological conditions since deposition. So far we do not have the capability to simulate the resuspension of mineral dust with ICON-ART. We believe that this process is of minor importance for our target region Germany. Therefore it is not in the focus of the current study.

However, it is a working package in our project PerduS, to parameterize the pollution of the PV panels due to dry and wet deposition as well as the cleaning effect of subsequent precipitation events. To be able to do this, one ingredient is to implement the aforementioned bookkeeping of the deposited mineral dust.

9) Some typos to check and correct (not all, just examples): p.2, l25: its influcence p.6, l.6: kinetic energye

The transport of mineral dust and its influence on atmospheric composition and radiation are not explicitly considered within conventional numerical weather prediction.

These percentages of kinetic energy are chosen such that particles in the largest mode are emitted first when the threshold friction velocity is exceeded.

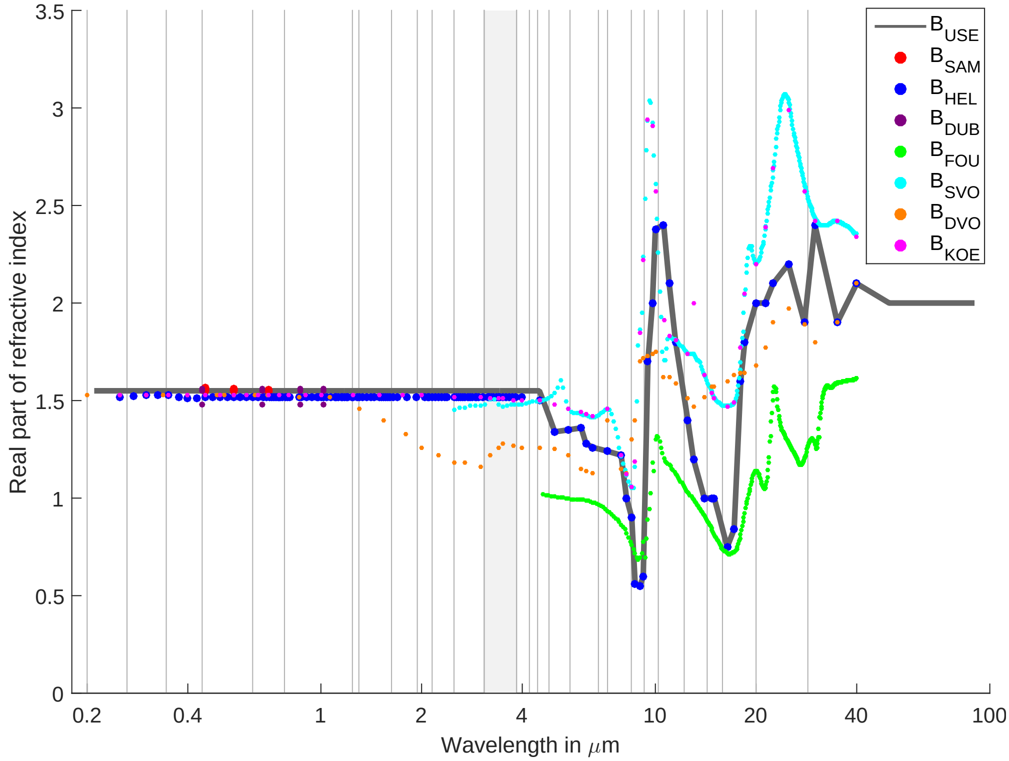

Figure 1. Real part of refractive indices according to studies listed in Tab. 2 and as used in ICON-ART (B_{USE}). The borders of the RRTM radiation scheme wavebands are adumbrated as light grey lines in the background. The filled grey band represents the waveband present both in the longwave and shortwave part of the RRTM. Taken from Gasch (2016).

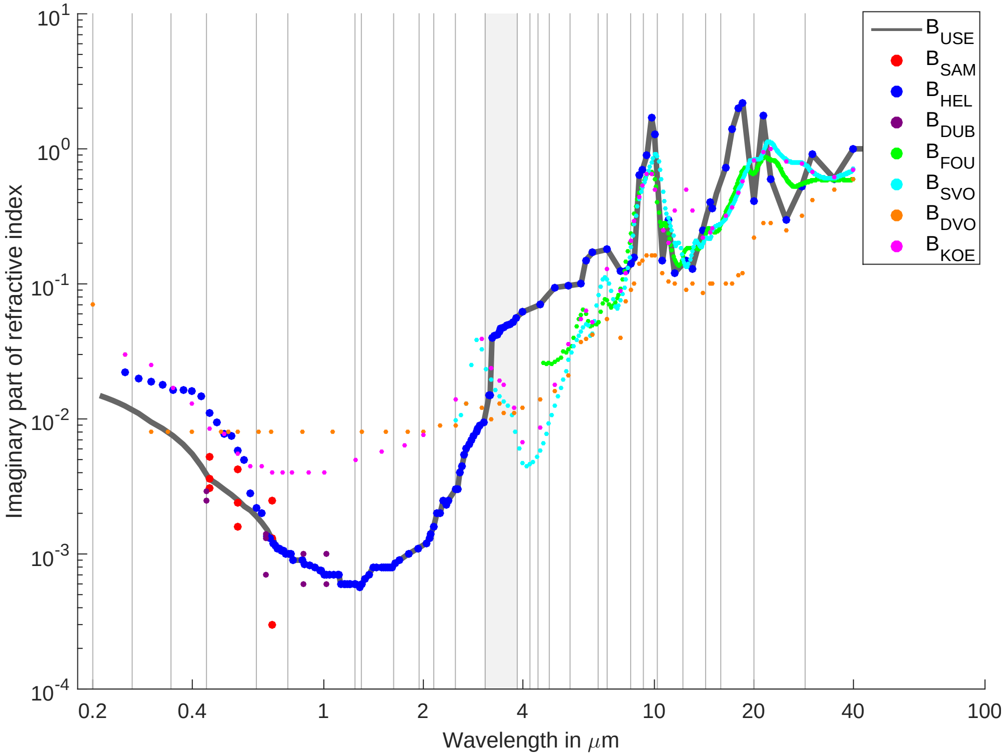

Figure 2. Same as Fig. 1, but for the imaginary part of refractive indices. Taken from Gasch (2016).

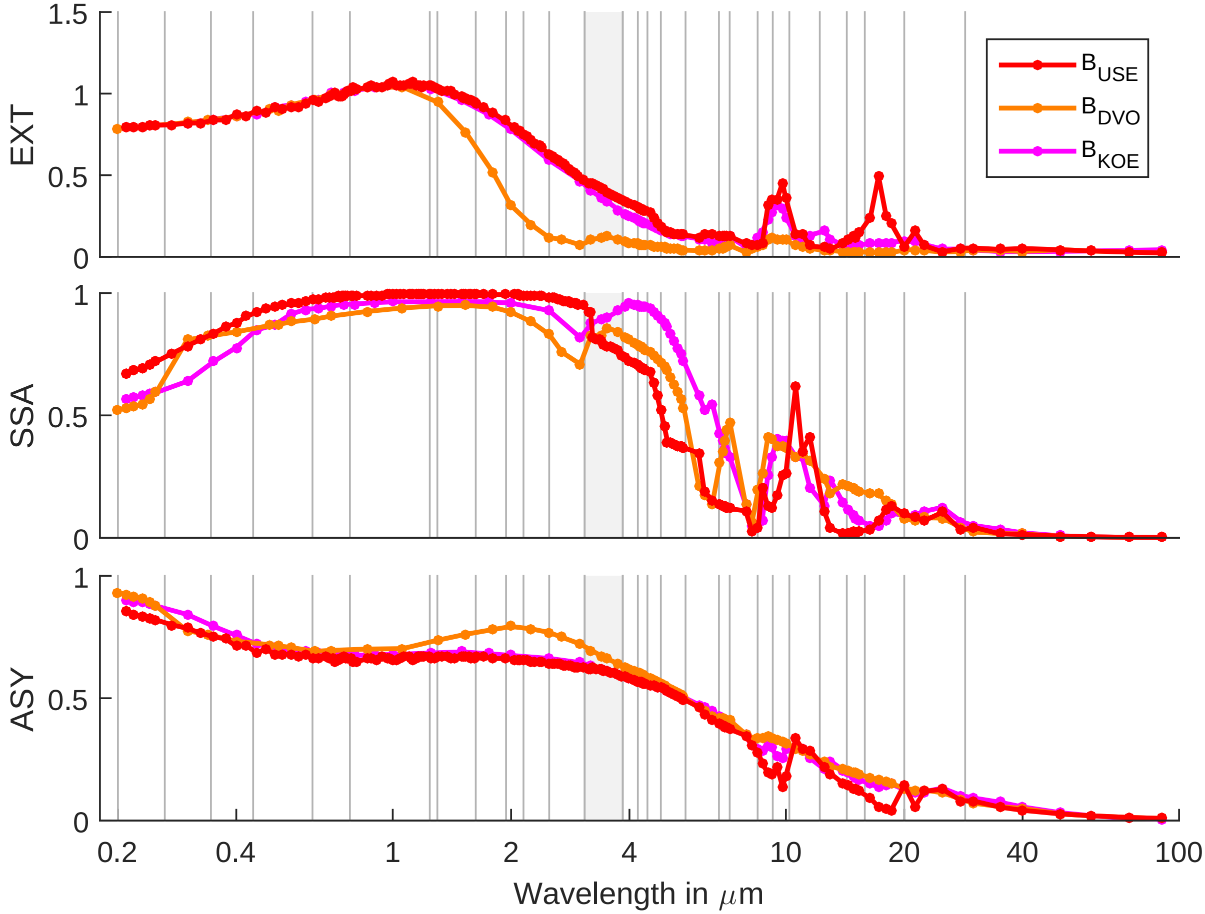

Figure 3. Influence of differences in refractive indices on optical properties for mode A. Taken from Gasch (2016).

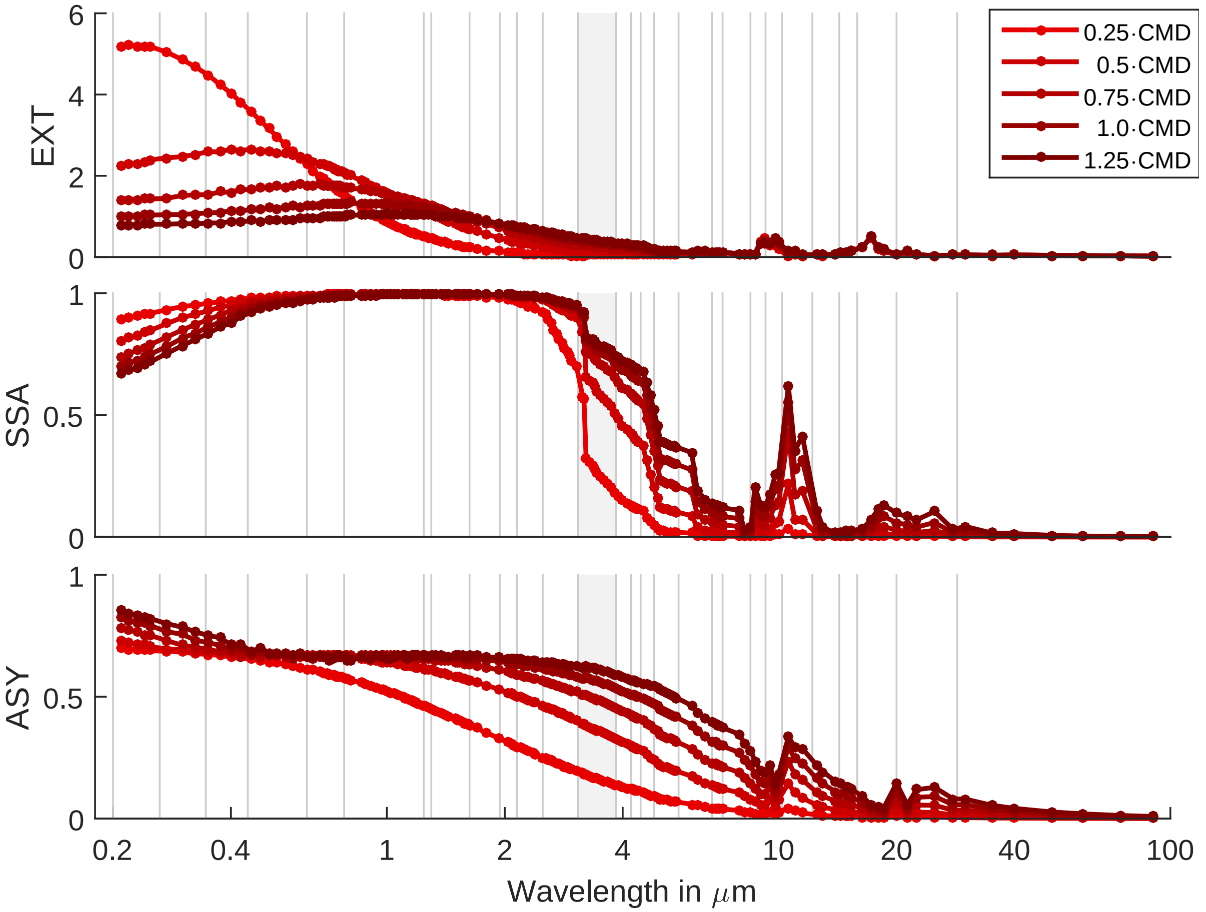

Figure 4. Influence of varying median diameter on optical properties for mode A. Taken from Gasch (2016).

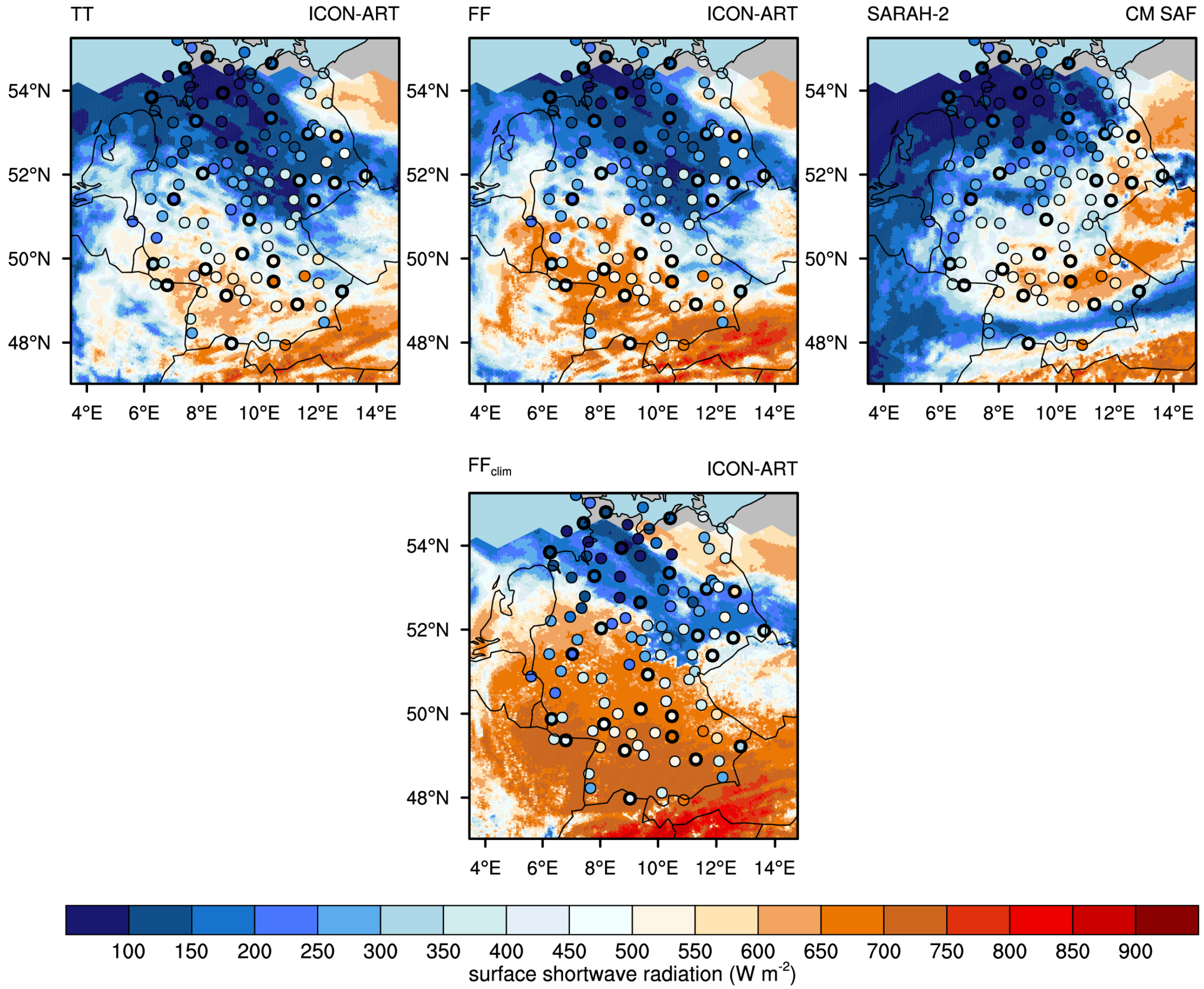

Figure 5. SIS of TT (left), FF (middle), SARAH-2 dataset by CM SAF (right) and FF_{clim} (second line) on 4 April 2014 at 12:30 UTC in Germany. Dots: SIS at SYNOP (thin circle lines) and pyranometer stations (thicker circle lines).

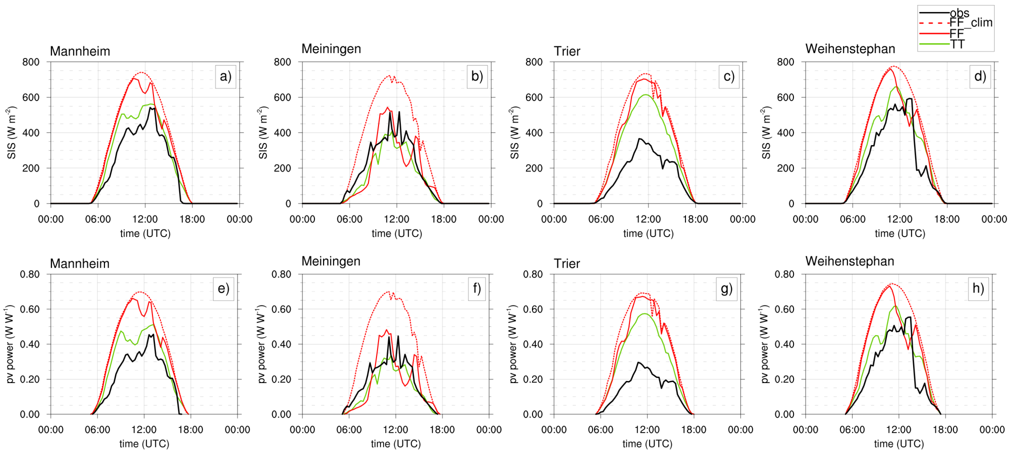

Figure 6. Comparison of observed (black, by pyranometer) and simulated (TT in green, FF in red and FF_{clim} in dashed red) surface incoming shortwave irradiance (SIS, a-d) and the resulting computed normalized PV power (e-h) for the stations Mannheim, Meiningen, Trier and Weihenstephan on 4 April 2014, respectively. The normalization is done with respect to peak power.

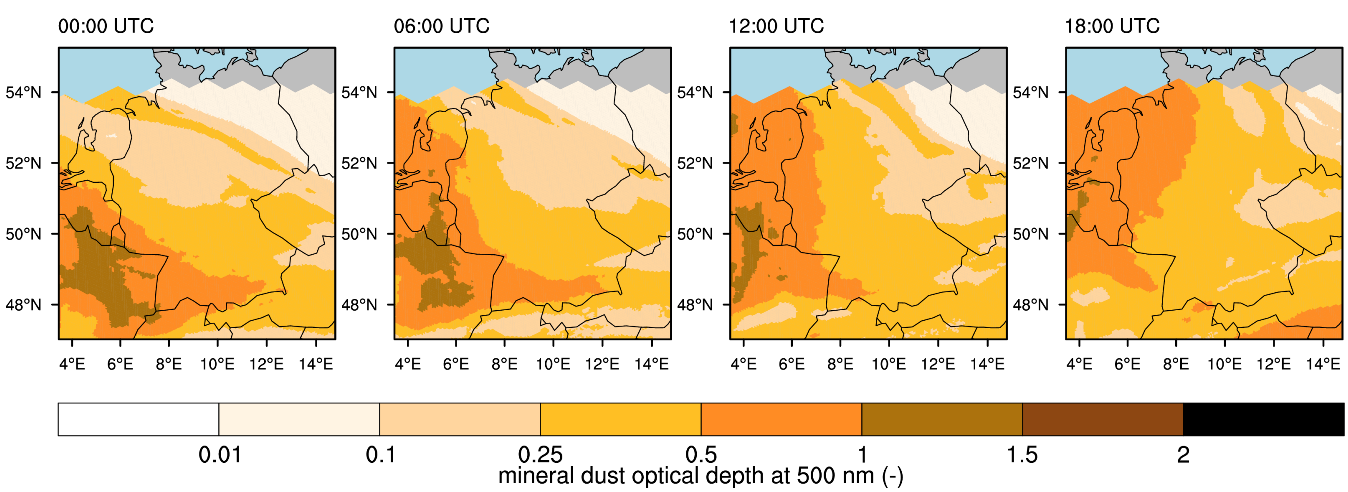

Figure 7. Mineral dust optical depth at 500 nm over Germany on 4 April 2014 at 00 UTC, 06 UTC, 12 UTC and 18 UTC (TT case). Note the saw-tooth shape in the northern part which marks the margin of the high resolution (5 km) domain and must not be confused with mineral dust-free conditions.

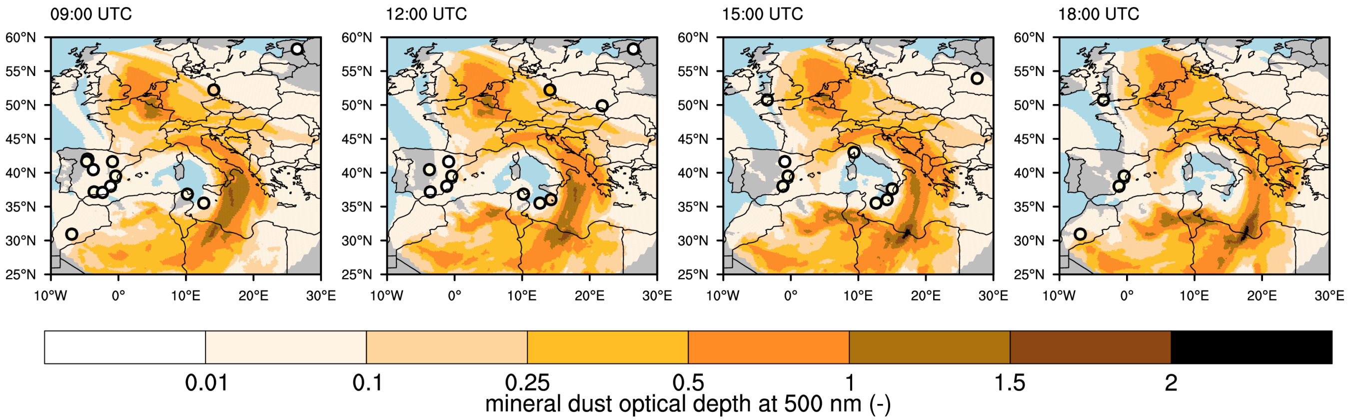

Figure 8. Mineral dust optical depth at 500 nm over Europe on 4 April 2014 at 09 UTC, 12 UTC, 15 UTC and 18 UTC (TT case) at 20 km grid spacing. The filled circles represent observations from AERONET stations. Note the saw-tooth shape next to the boarders which marks the margin of nest R2B07 and must not be confused with mineral dust-free conditions.

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