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Investigating the sensitivity to resolving aerosol interactions in downscaling regional model experiments with WRFv3.8.1 over Europe

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Abstract.

In this work we present downscaling experiments with the Weather Research and Forecasting model (WRF) to test the sensitivity to resolving aerosol-radiation and aerosol-cloud interactions on simulated regional climate for the EURO-CORDEX domain. The sensitivities mainly focus on the aerosol-radiation interactions (direct and semi-direct effects) with 4 different aerosol optical depth datasets (Tegen, MACv1, MACC, GOCART) being used and changes to the aerosol absorptivity (single scattering albedo) being examined. Moreover part of the sensitivities also investigates aerosol-cloud interactions (indirect effect). Simulations have a resolution of 0.44° and are forced by the ERA-Interim reanalysis. A basic evaluation is performed in the context of seasonal-mean comparisons to ground based (E-OBS) and satellite-based (CMSAF SARAH, CLARA) benchmark observational datasets. Implementation of aerosol-radiation interactions reduces the direct component of the incoming surface solar radiation by 20-30% in all seasons, due to enhanced aerosol scattering. Moreover the aerosol-radiation interactions increase the diffuse component of surface solar radiation in both summer (30-40%) and winter (5-8%) whereas the overall downward solar radiation at the surface is attenuated by 3-8%. The resulting aerosol radiative effect is negative and comprises of the net effect from the combination of the highly negative direct aerosol effect (-17 to –5 W/m^2) and the small positive changes in the cloud forcing (+5 W/m^2), attributed to the semi-direct effect. The aerosol radiative effect is also stronger in summer (-12 W/m^2) than in winter (-2 W/m^2). We also show that modeling aerosol-radiation and aerosol-cloud interactions can lead to small changes in cloudiness, mainly regarding low-level clouds, and circulation anomalies in the lower and mid-troposphere, which in some cases can be statistically significant. Precipitation is not affected in a consistent pattern by the aerosol implementation and changes do not exceed $\pm$ 10% . This result is in contrast to other regional downscaling studies investigating either aerosol-radiation or aerosol-cloud interactions. Temperature, on the other hand, systematically decreases by -0.1 to -0.5°C due to aerosol-radiation interactions with regional changes that can be up to -1.5°C.

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1 Introduction

Aerosols play an important role in the Earth's climate system due to their substantial effects on the radiation budget and cloud properties (Ramanathan et al., 2001). The 5th Climate assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Boucher et al., 2013) identifies aerosols together with clouds as the largest sources of uncertainty in the Earth's climate system. This is mainly due to the effects of radiative forcing from aerosol-radiation (ari) and aerosol-cloud interactions (aci), including the radiative forcing and adjustments. In the regional climate model experiments of the Coordinated Regional Climate Experiment (CORDEX) (Giorgi and Gutowski, 2015) covering the European and Mediterranean regions (EURO-CORDEX, MED-CORDEX), aerosols are treated differently in the various participating modeling systems. Within the MED-CORDEX community there have been several studies highlighting the impacts of aerosols (Ruti et al., 2016). The considerable impact of the aerosol direct and semi-direct effects on the climate of the Euro-Mediterranean region has been clearly demonstrated (Nabat et al., 2015). Moreover, long-term trends in aerosol concentrations have been linked to observed trends in temperature and radiation over the Euro-Mediterranean region (Nabat et al., 2014) that cannot be reproduced without considering aerosol effects in RCM simulations. Inclusion of aerosol representation is also considered essential in solar energy generation (Gutiérrez et al., 2018). Within EURO-CORDEX co-ordinated experiment the treatment of aerosol depends on the modeling system and on the model setup[1] : the majority of the models participating in the experiment takes aerosols into account by using aerosol climatologies either in a time-invariant manner or with monthly variations that partly include trends while a few models do not include aerosols at all. Finally, a minority of the simulations use prognostic aerosol schemes with natural and anthropogenic emissions (dust, sea salt) online driven by meteorology. The sophistication of the aerosol-cloud-radiation implementation also varies between modeling system: while most regional climate models account for aerosol-radiation interactions (direct and semi-direct aerosol effect), the aerosol-cloud interactions (indirect aerosol effect) is typically not considered. The aerosol climatologies, used by the majority of the models, are not consistent and some models use outdated datasets. In a modeling study over Europe Zubler et al. (2011) has shown that changing to newer aerosol climatologies can have a significant impact on model results, specifically on shortwave radiation at the surface. Schultze and Rockel (2018) have also shown improvement of model performance when using newer aerosol climatologies on long-term climate simulations over Europe. The Weather Research and Forecasting (WRF) model (Powers et al., 2017; Skamarock et al., 2008) has previously been used to explore the impact of aerosol on weather and climate patterns. Ruiz-Arias et al. (2014) introduced an aerosol-radiation interaction parameterization and tested it over the continental U.S. to investigate its impact on radiation. They concluded that the parameterization produces satisfactory results for predicting shortwave radiation at the surface and its direct and diffuse components. Moreover they demonstrated that the inclusion of aerosol-radiation interactions significantly reduces prediction errors in radiation under clear sky conditions, especially in simulating diffuse radiation. Furthermore the seasonality of the radiation bias is also improved when the seasonal variability of the aerosol optical depth is taken into account. Similar results were documented by Jimenez et al. (2016) by implementing aerosol-cloud-radiation feedbacks into WRF with the use of the new Thompson aerosol-aware cloud aerosol-cloud interacting scheme (Thompson and Eidhammer, 2014) that is computationally inexpensive enough to sup-

[1] https://docs.google.com/document/d/1UCCv-DU8hLlZaSPkcndnM0SrJHoX4cvG-yqxbIDZlRc/edit

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port operational weather and solar forecasting. This aerosol-cloud interaction option is available from WRF3 v3.6 onward. Da Silva et al. (2018) used this aerosol-cloud interacting cloud microphysics scheme in WRF to estimate the aerosol indirect effect and its impact on summer precipitation over the Euro-Mediterranean region, concluding that higher aerosol loads lead to decreased precipitation amounts. Here we use the WRF model, which is widely used for regional climate simulations over Europe (Katragkou et al., 2015). The scope of this paper is to first evaluate model simulations without aerosol treatments (section 3.2) and then examine the impact of different aerosol parameterizations and model configurations as well as aerosol climatologies on the European climate (section 3.3). We examine various radiation components, which are commonly not examined in RCM simulations (total, clear sky, direct, diffuse radiation), clouds, temperature and precipitation.

2 Data and Methodology

2.1 Observational Data

2.1.1 Temperature and precipitation

The evaluation of the model simulations for temperature (2m) and precipitation is performed against the E-OBS v16 dataset (Haylock et al., 2008). Daily mean values are used covering the EURO-CORDEX domain (25S-75N, 40W-75E) on a 0.44^{o} rotated pole grid. It is a gridded dataset with good spatial and temporal coverage, however, as with all datasets, it is not without limitations. When compared against regional datasets with higher station density (Hofstra et al., 2009) the E-OBS dataset presented a mean absolute error around 0.5^{o}C for temperature whereas for precipitation it exceeded in cases 100% with a general tendency of underestimating precipitation amount. Moreover Prein and Gobiet (2017) showed that uncertainties in European gridded precipitation observations are particularly large in mountainous regions and snow dominated environments.

2.1.2 Radiation

Shortwave downwelling radiation flux at the surface (Rsds) and Direct Normalized Irradiance at the surface (DNI) are compared against the Surface Solar Radiation Data Set - Heliosat (SARAH)-Edition1. The SARAH dataset is based on satellite observations coming from the MVIRI and SEVIRI instruments onboard the geostationary Meteosat satellites (Müller et al., 2015). SARAH is available as hourly, daily and monthly averages on a regular grid with a high spatial resolution of 0.05° x 0.05° from 1983 to 2013 between ± 65° longitude and ± 65° latitude. Here we use monthly values. Another satellite product used for Rsds evaluation in this study is the CLARA-A1 dataset (Karlsson et al., 2013). This is a global dataset which contains a number of cloud, surface albedo and surface radiation products. In contrast to the SARAH dataset, CLARA is based on observations from polar orbiting NOAA and Metop satellites carrying the Advanced Very High Resolution Radiometer (AVHRR). It covers the period from 1982 to 2009 globally on a regular 0.25 degree spacing latitude-longitude grid. Both SARAH and CLARA-A1 satellite datasets were obtained from CMSAF (Satellite Application Facilities for Climate Monitoring), which is part of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). SARAH has less missing values, better accuracy (< 5W/m^2) and less estimated uncertainty (<10W/m^2) for Rsds compared to the CLARA dataset (Karls-

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son et al., 2013; Müller et al., 2015). According to our analysis discrepancies between the two datasets do not generally exceed 15% for most subregions and seasons. Larger differences can be found in Scandinavia during winter, possibly related to its high latitude, which can be challenging for geostationary satellites as those used in SARAH (Schulz et al., 2009), and to the high albedo due to extensive snow coverage. Since relative differences between the two sets are small, and spatial correlation is quite high (0.95 to 0.98 depending on season) we only use the Rsds observations from the SARAH dataset for model evaluation.

2.1.3 Cloud fraction

Here cloud fraction means total column cloud fraction. Our primary source of cloud fraction data is the CLARA-A1 satellite dataset described above (section 2.1.2). In an evaluation (Karlsson and Hollmann, 2012) against global synoptic cloud observations (for the period 1982-2009) the CLARA cloud fraction product has shown a small overestimation of 3.6% whereas against satellite-based observations from the CALIOP/ CALIPSO instrument (for the period 2006-2009) it exhibited and underestimation of -10% .

2.1.4 Aerosol optical depth

In order to assess the aerosol data used in our simulations (section 3.1) we compare aerosol optical depth (AOD) at 550nm against AOD estimates of the CMSAF climate data record (Clerbaux et al., 2017). This dataset is derived from measurement of the SEVIRI instrument, on the Meteosat Second Generation satellite, after the incorporation of the Land Daily Aerosol (LDA) algorithm. Monthly AOD estimates have been used for this study.

2.2 Model

All simulations in this work are performed with WRF/ARW (version 3.8.1) model (Skamarock et al., 2008; Powers et al., 2017). The domain covers Europe (25S-75N, 40W-75E) with a resolution of 0.44^o ($\sim$ 50km) following the EURO-CORDEX specifications (Giorgi and Gutowski, 2015) and domain setup. The simulations are forced by the ERA-Interim reanalysis (Dee et al., 2011) while the same dataset is used for the imposed sea surface temperature (SST) variations. The model has 133X130 grid points and 31 vertical levels reaching up to 50 hPa with a 9 grid cells relaxation zone at the model top. The selected time period for the sensitivity study extends from 2004 to 2008 (2003 used as spin up time) to allow for comparison with the EUMETSAT satellite datasets. All simulations are conducted with the same model setup and parameterizations with the only differences being the aerosol options and aerosol data used (see details in section 2.4).

In our regional climate modeling sensitivity experiments, we use the Thompson cloud microphysics scheme (Thompson et al., 2008) in six simulations and the Thompson aerosol-cloud interacting cloud microphysics scheme (Thompson and Eidhammer, 2014) in two simulations (Table 1). The aerosol-cloud interacting scheme is based on the Thompson bulk scheme, which is double moment regarding cloud ice and rain and uses five hydrometeor species: cloud water, cloud ice, rain, snow and graupel. The aerosol-cloud interacting scheme incorporates aerosol in the microphysical processes, thus enabling aerosol-cloud interactions (indirect aerosol effect) which are absent in the previous Thompson (2008) cloud microphysics scheme.

All simulations use the land surface model CLM4 (Lawrence et al., 2011; Oleson et al., 2010), the planetary boundary layer scheme from the Yonsei University (Hong et al., 2006), the revised-MM5 surface layer option (Jiménez et al., 2012) and the Grell-Freitas cumulus scheme (Grell and Freitas, 2014). The RRTMG (Iacono et al., 2008) radiation scheme is used to simulate short and longwave radiation, which is compatible with the aerosol-radiation interaction implementation in the aerosol-cloud interacting Thompson cloud microphysics scheme. Model cloud fraction has been calculated using the method described in (Sundqvist et al., 1989) (icloud=3 option in the namelist). This is based on a threshold of relative humidity (RH) which is affected by the grid size. The "cu_rad_feedback" flag is also enabled to allow sub-grid cloud fraction interaction with radiation (Alapaty et al., 2012).

2.3 WRF Aerosol options and input data

2.3.1 WRF Aerosol options

The WRF model provides three main aerosol options encompassing aerosol-radiation interactions. The first,(aer_opt=1 in the namelist) uses the aerosol input climatology of Tegen et al. (1997). The spatial resolution of the data is coarse (5 degrees in longitude and 4 degrees in latitude) and temporal changes throughout the year are included as monthly variations. For its implementation in WRF, AOD is provided in each vertical model level, as an aggregate of the five aerosol types taken into account (organic carbon, black carbon, sulfate, sea salt and dust).

The second aerosol-radiation option (aer_opt=2) (Ruiz-Arias et al., 2014) enables the user to provide aerosol input data. The user can either provide non-variable aerosol properties in the namelist or an external aerosol data file with spatial and temporal aerosol variations. In the latter option, the user must provide the total column aerosol optical depth (AOD) at 550nm and can either choose to provide other aerosol optical parameters (single scattering albedo (SSA), the asymmetry factor (ASY) and Angstrom exponent (AE)) or can choose to parameterize one or all of them through selecting a certain "aerosol type" in the namelist. There are three aerosol types available, rural, urban and maritime. In this work the first two options have been implemented. The "rural" option considers aerosols as a mixture of 70% water soluble and 30% dust aerosols. The "urban" type consists of 80% of the above "rural" type aerosols mixed with 20% soot aerosols, thus making it considerably more absorbing. Finally, the vertical distribution of aerosol AOD is described with a prescribed exponential profile. This is adequate for assessing the impact of total aerosol load on the radiation at the surface, but studying aerosol-radiation interactions at vertical levels (possible semi-direct effect) would be incomplete with this assumption. Using the second aerosol option (aer_opt=2) we conducted simulations with two aerosol datasets.

The third aerosol option (aer_opt=3) enables aerosols to interact with radiation within the Thompson aerosol-cloud interacting cloud microphysics scheme. It is based on the second aerosol-radiation option described above using the "rural" aerosol type. Further information about the aerosol of the new Thompson aerosol-cloud interacting cloud microphysics can be found in the next paragraph 2.3.2

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2.3.2 Aerosol data

We use two external aerosol datasets. The first is the Max-Planck-Institute Aerosol Climatology version 1 (MAC-v1) (Kinne et al., 2013). The MAC-v1 is a global climatology of aerosol that has been produced by combining global aerosol models and ground-based measurement by sun-photometer networks. Aerosol optical properties are provided on a global scale at a spatial resolution of 1 degree. Monthly data regarding total, as well as anthropogenic aerosol properties, are available ranging from preindustrial times to the end of 21^{st} century. We use a part of this climatology that contains the merging of monthly statistics of aerosol optical properties to describe current conditions.

The second dataset used is the MACC reanalysis (Inness et al., 2013). Data are provided globally at a horizontal resolution of about 80 km for the troposphere and the stratosphere (Inness et al., 2013). An advantage of the MACC dataset is its daily resolution. A study that tested different climatologies (Mueller and Träger-Chatterjee, 2014), including MAC-v1 and a climatology based on the MACC reanalysis concluded that the MACC climatology leads to the highest accuracy in solar radiation assessments.

The new Thompson aerosol-cloud interacting cloud microphysics scheme has an internal treatment of aerosols. Aerosols are separated into cloud droplet nucleating acting as cloud condensation nuclei (CCNs), and cloud-ice nucleating, acting as ice nuclei (IN). Cloud-droplet nucleating aerosols include sulfates, sea salt and organic carbon. Cloud-ice nucleating aerosols include dust larger than 0.5 μ m. Black carbon is not included. Aerosol initialization and boundary conditions are based on an aerosol climatology constructed from global simulations spanning the period 2001-2007 (Colarco et al., 2010) with the use of the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Ginoux et al., 2001). The two categories of aerosols are then advected and diffused during the model run. Furthermore, a field representing cloud-droplet nucleating surface aerosol emission flux is introduced to the lowest model level at each time step. Surface emission flux is based on initial aerosol concentrations at the surface and on a constant value of mean surface wind. The aerosols can be allowed to interact with radiation (aer_opt=3), enabling aerosol-radiation interactions in addition to the existing aerosol-cloud interactions, thus providing a complete representation of aerosol interactions.

2.4 Model Simulations

Using the above aerosol options and datasets we performed 7 sensitivity experiments from a control run with no aerosol interactions covering the period 2004-2008.

– The control experiment (CON) does not include aerosol-radiation or aerosol-cloud interactions (aer_opt=0), meaning the simulation is aerosol-insensitive.

– The second simulation including aerosol-radiation interactions (ARI_T) uses the Tegen (1997) climatology (aer_opt=1).

The next four experiments, also only account for aerosol-radiation interactions and use the methodology introduced by Ruiz-Arias, Dudhia, and Gueymard (2014) (aer_opt=2):

– ARI_Mv1 uses AOD from the MACv1 climatology and the “rural” aerosol type.

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- ARI_Mv1urban uses AOD from the MACv1 climatology as well but assigns all aerosols to the more absorbing "urban" aerosol type.

- ARI_Mv1full uses AOD, single scattering albedo (SSA) and asymmetry factors (ASY) from the MACv1 climatology together with the "rural" aerosol type to parameterize only the Angstrom exponent (AE).

- ARI_MC uses the MACC aerosol optical depth dataset and the "rural" aerosol type.

All of these simulations use the Thompson (mp=8) aerosol-cloud interacting cloud microphysics scheme which will be referred to as the Thompson2008 scheme. It must be noted here that implementation of aerosol-radiation interactions in a simulation enables the impact of both the direct and the semi-direct aerosol effect. The single scattering albedo (SSA) at 550nm of the ''rural" type aerosols ranges in our experiments between 0.92 and 0.98 whereas the ''urban" type is much more absorbing with SSA starting as low as 0.6, values that are considered unrealistic (Rodriguez et al., 2013; Tombette et al., 2008; Witte et al., 2011). Therefore the ARI_Mv1urban simulation must be considered as an idealized experiment of extremely absorbing aerosols.

Two additional simulations (ACI, ARCI) have been performed using the new Thompson aerosol-cloud interacting cloud microphysics scheme (mp=28), which enables the aerosol indirect effect.

- The ACI simulation does not consider aerosol-radiation interactions.

- Simulation ARCI includes both aerosol-radiation and aerosol-cloud interactions with the passing of effective radii from the aerosol-cloud interacting cloud microphysics to the radiation scheme. This simulation presents the most complete physical description of aerosol effects in the simulation ensemble.

All the simulations, aerosol sources and options used are presented in Table 1. The simulations that account for aerosol-radiation interactions are symbolized with ARI in their names. The simulation with the Thompson aerosol-cloud interacting scheme that accounts for aerosol-cloud interactions is symbolized as ACI whereas the experiment that accounts both for aerosol-radiation and aerosol-cloud interactions is symbolized as ARCI. The simulations that account only for aerosol-radiation interactions will be referred to as the ARI group of experiments. Finally, for brevity, the Thompson aerosol-cloud interacting scheme is referred to as TE2014 hereafter.

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Table 1. Simulations conducted and description of aerosol treatment

Simulation	CON (Control)	ARI_T	ARI_Mv1	ARI_Mv1urban	ARI_Mv1full	ARI_MC	ACI	ARCI
Cloud micro-physics scheme	Thompson 2008	Thompson 2008	Thompson 2008	Thompson 2008	Thompson 2008	Thompson 2008	TE2014	TE2014
Aerosol option	-	aer_opt=1	aer_opt=2	aer_opt=2	aer_opt=2	aer_opt=2	aer_opt=0	aer_opt=3
Aerosol source	-	Tegen	MACv1	MACv1	MACv1	MACC	GOCART	GOCART
User input data	-	No input by user	AOD,"rural" aerosol type	AOD,"urban" aerosol type	AOD,SSA, ASY "rural" aerosol type	AOD,"rural" aerosol type	-	-
Aerosol interacting with	-	radiation	radiation	radiation	radiation	radiation	clouds	radiation + clouds

2.5 Methodology

We analyze the following variables: temperature at 2m, precipitation, shortwave down welling radiation at the surface (Rsds), direct normalized irradiance at the surface (DNI), diffuse irradiance at the surface (DIF), total cloud fraction (CFRACT) and the wind field at various pressure levels. Besides total column cloud fraction we also examine cloud fraction regarding low (<2.5 km), medium (2.5<z<6 km) and high (>6 km) level clouds. Cloud fraction for each level, as well as for the total column, is calculated using the random overlapping method where the total cloud fraction C_{rand} for two layers is considered as: C_{rand}= c_a+c_b-$c_a c_b$ where c_a, c_b are the cloud fraction in each layer (Hogan and Illingworth, 2000).

We also calculate the following metrics:

1. The radiative effect of aerosol on shortwave radiation at the surface (RE). It is the difference in net shortwave radiation at the surface (netRsds) between an aerosol simulation and the CON experiment. Thus:

$$RE = netRsds_{Aerosol} - netRsds_{Control} \qquad (1)$$

2. The direct radiative effect of aerosol on shortwave radiation at the surface under clear-sky conditions (DRE). This is the difference in net clear-sky shortwave radiation at the surface (netCRsds) between an aerosol simulation and the CON

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experiment. Thus:

$$DRE = netCRsds_{Aerosol} - netCRsds_{Control} \tag{2}$$

Since the DRE is calculated under clear-sky conditions it encompasses only the direct aerosol effect and not the semi-direct effect.

3. The effect of clouds on shortwave radiation at the surface (SCRE). It is the difference of the net shortwave radiation at the surface (netRsds) and the net clear-sky shortwave radiation at the surface (netCRsds) for a given experiment:

$$SCRE = netRsds - netCRsds \tag{3}$$

4. In order to assess the impact of the aerosol implementation on the radiative effect of clouds the difference of SCRE (ΔSCRE) is calculated between an aerosol experiment and CON. Therefore:

$$\Delta SCRE = SCRE_{Aerosol} - SCRE_{Control} = RE - DRE \tag{4}$$

When comparing the group of simulations that account for the aerosol-radiation interactions only with CON the calculated ΔSCRE accounts for the semi-direct effect of aerosols.

Regarding all the variables examined, in order to assess the impact of aerosol implementation we always compare the aerosol-interacting simulation to the non-interacting control simulation CON. To assess the impact of the aerosol-radiation interactions and the impact of different aerosol parameterizations, we compare the simulation family ARI, which use the Thompson2008 scheme, to CON. Comparison of the simulation ACI to CON indicates the impact of the Thompson aerosol-cloud interacting cloud microphysics scheme which implements the indirect aerosol effect. Comparison of ARCI to CON indicates the impact of both aerosol-radiation interactions and the Thompson aerosol-cloud interacting coloud microphysics scheme. Finally the only situation when a comparison is not performed against CON is when comparing ARCI to ACI, both using the aerosol-cloud interacting Thompson cloud microphysics. This enables to assess the aerosol direct and semi-direct effect under an environment where the indirect effect is also present.

The main metrics used for evaluation are Bias (model-reference), Absolute Bias (| model-reference|) and relative Bias ((model-reference)/reference)$*$ 100. Correlation coefficients between two datasets are computed using the linear Pearson correlation coefficient. Statistical significance is calculated at the 0.05 level with the Mann-Whitney non-parametric test since many of the variables examined deviate from a normal distribution. Mean daily values are used in the above tests since the time span of the simulations is not sufficient for the use monthly or seasonal values.

In order to enable grid cell comparisons of the model output against observations we use distance weighted average remapping using the four nearest neighbor values. We always remapped the finer grid onto the coarser. Therefore, all satellite products were remapped onto the WRF 0.44^{o} grid, whereas temperature and precipitation model output was remapped onto the E-OBS

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0.44° rotated grid. Furthermore, simulated temperature has been corrected with respect to the E-OBS elevation, using a temperature lapse rate of 0.65 K/km throughout the domain.

We analyze our data over the whole European domain, which we define as the as the region that consists of the Prudence subregions (Christensen et al., 2007) thus lying between -10° and 40°in longitude and 36° to 70° in latitude. Furthermore, the analysis is conducted on a seasonal basis for all four seasons of the year, winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Seasonal averages are computed using mean monthly values.

3 Results

3.1 Aerosol optical depth

The mean seasonal fields of aerosol optical depth (AOD) at 550nm used (or produced in the case of Thompson aerosol-cloud interacting scheme) in our experiments can be seen in Fig. 1 together with the AOD field of CM SAF SEVIRI satellite product for comparison. The fields of both simulations using the Thompson aerosol-cloud interacting scheme are very similar thus only the AOD of ARCI is presented.

The climatology of Tegen has a lower AOD compared to SEVIRI, but follows the latter's seasonal spatial variability. MACv1 has a central European local maximum in JJA, which is not discernible in any other AOD product and overestimates the North African dust component in spring. The MACC reanalysis agrees best with the satellite data. Finally, the Thompson aerosol optical depth has a couple of spurious features: the Eastern European AOD maximum in spring and the higher generally higher AOD in colder months (DJF and SON) compared to all other products.

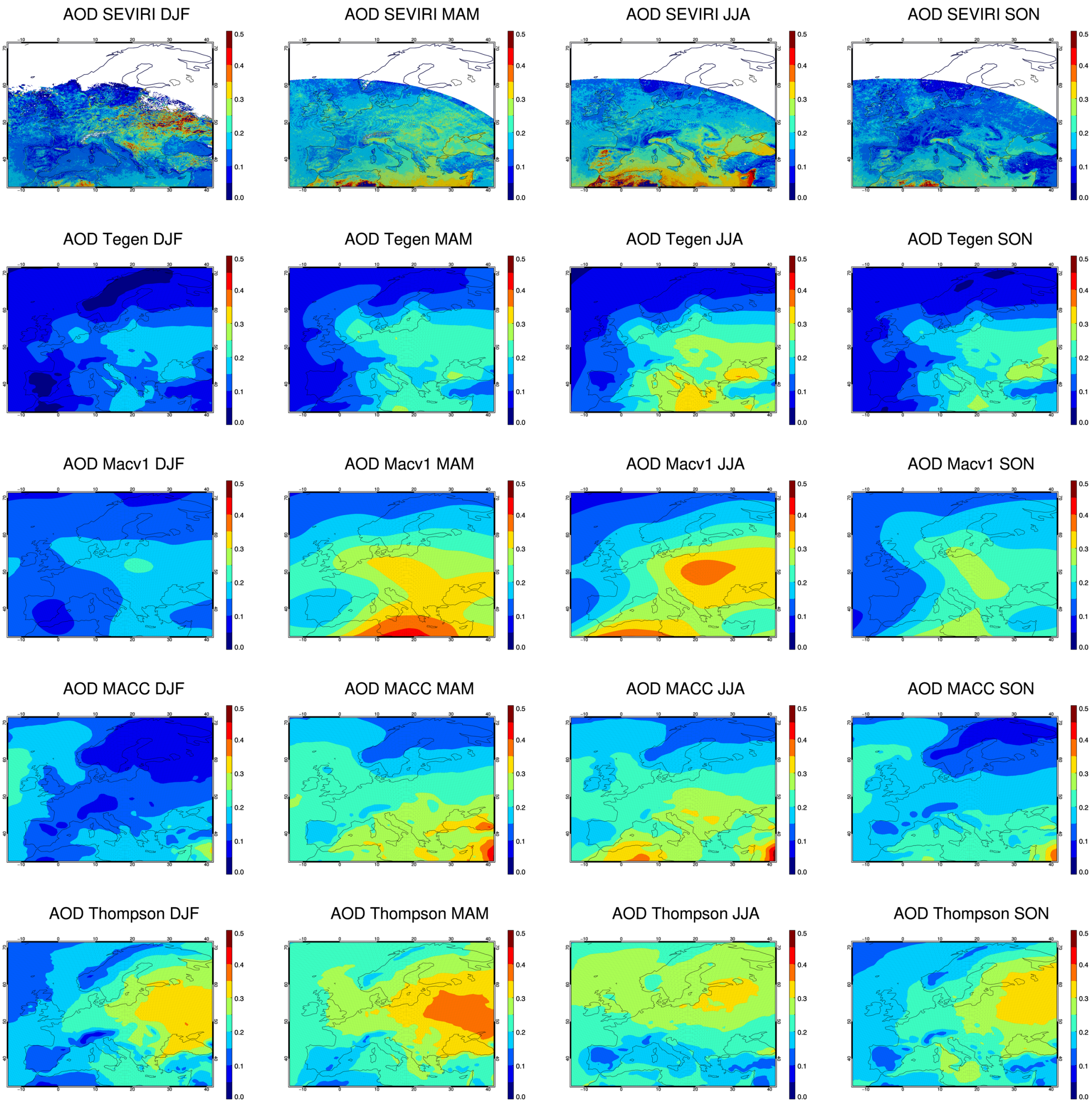

Figure 1. Mean seasonal aerosol optical depth at 550nm for (from top to bottom) the CM SAF record, the Tegen climatology, the MACv1 climatology, the MACC reanalysis and the ARCI simulation produced by the Thompson aerosol-cloud interacting scheme.

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3.2 Evaluation of the Control Simulation

Despite some biases the control simulation (CON) captures the basic features of the European climate, which in turn indicates that the main physical processes are represented with a reasonable degree of fidelity, thus increasing the confidence on the sensitivity results.

3.2.1 Temperature

In the simulation CON winter temperatures are mostly underestimated (-0.5°C domain average, land only), with higher cold biases over Scandinavia, the Mediterranean and the Alps (-1°C) as indicated in the upper panel of (Fig. 2). Winter cold biases especially over northern Europe are common in many EURO-CORDEX simulations (Kotlarski et al., 2014). In this study winter biases are reduced in comparison to previous WRF exercises in EURO-CORDEX hindcast experiments (Katragkou et al., 2015). Since many of these WRF studies implement the Noah land surface model, we contend that the use of the CLM land surface model in this study is a factor for the reduced cold bias. Especially since northern Europe is largely covered with snow during winter and the treatment of the snowpack by the land scheme is of particular importance. Also summer features a cold bias over most of the domain (-0.5°C domain average) with a tendency for minor warm biases in south and Eastern Europe. This bias pattern - cold in the north and warm in the south - has been detected in other RCM simulations over Europe such as RCA4, CCLM4, HIRHAM (Kotlarski et al., 2014).

3.2.2 Precipitation

Winter precipitation is overestimated throughout the domain (43% domain average), with pronounced biases existing over central (+50%) and especially over Eastern Europe, locally exceeding 100% (Fig. 2). Wet biases during DJF in Eastern Europe are common in WRF simulations (Katragkou et al., 2015; García-Díez et al., 2015; Mooney et al., 2013). The current parameterization (CON) seems to amplify the commonly simulated wet bias in the eastern part of Europe during winter. In summer biases are smaller and mostly dry (-3% domain average), which is not very typical for WRF, with most subregions presenting underestimation around -20 to -30% . However, areas with high positive relative biases are seen at the southern parts of Europe, where precipitation amounts are very small during the warm months which amplifies the relative biases. The above winter/summer bias patterns are seen in both cloud microphysics schemes used, the Thompson in CON and Thompson aerosol-interacting. An additional simulation conducted using the WDM6 cloud microphysics (not shown) yielded very similar results regarding precipitation bias indicating that the cloud microphysics scheme is not the main cause of precipitation bias.

3.2.3 Cloud fraction

Cloud fraction is overestimated in winter at 0.17 (+35%). The relative increase is more pronounced over the Iberian Peninsula (+60%) (Fig. 2, 3rd panel). In summer, the average overestimation is lower (0.08 or 12%) but there is a zonal pattern with ∼ 30% overestimation in northern Europe and a 10 % underestimation in the Mediterranean region. However, relative biases have to be interpreted with caution in southern Europe during summertime because of the small cloud fraction amount. For both

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seasons similar spatial patterns, including the bias magnitudes, have been observed in other WRF simulations (Katragkou et al., 2015; García-Díez et al., 2015). In the study of Katragkou et al. (2015), the WRF simulations that had a higher cloud fraction overestimation over the northern part of the domain were the ones implementing the Grell-Devenyi cumulus parameterization. The Grell-Freitas scheme used in this study is similar to the Grell-Devenyi scheme, consequently cloud overestimation in our case could be to some extent linked to the cumulus parameterization selection, especially during summer.

3.2.4 Shortwave radiation to the surface and direct normalized irradiance

Shortwave downwelling radiation at the surface (Rsds) averaged for the entire European domain is underestimated for both winter and summer. In winter Rsds is in general slightly underestimated (-4% average), with some subdomains like Mid-Europe, France and British Isles reaching -20 to -40% . In summer the domain averaged Rsds underestimation is approximately -8% . Larger negative biases are seen in the north and decrease in intensity as we move to the south following quite closely the cloud fraction bias pattern. The cloud and Rsds bias patterns are spatially correlated, as expected.

The bias pattern of direct normalized irradiance (DNI) is similar to that of Rsds but intensified. The underestimation in winter is around 13% whereas for summer the dual pattern of underestimation to the north (-20%) and overestimation to the south (20-30%) is even more pronounced.

In general, the aerosol-interacting simulations, implementing aerosol-radiation and/or aerosol-cloud interactions and the Thompson aerosol-cloud interacting cloud microphysics, present a similar behavior to the control simulation CON, regarding the biases of the main variables described above. This indicates that aerosol representation, despite its considerable impact seen in the next chapter, is not the main source of bias in our simulations. Moreover, aerosol introduction, despite making the representation of physical processes in the model more complete, often does not lead to bias improvements. Furthermore the improvement of bias does not necessarily mean that the aerosol representation is correct, since model biases can be the result of error compensation between errors in the aerosol representation and errors induced by other physical mechanisms. Zubler et al. (2011) in an RCM study (aerosol-climatology paper) reached similar conclusions, stating that the overestimation of aerosol optical depth was responsible for masking strong biases in the simulated cloud fraction. Figure S1 in the supplement presents the basic biases for simulation ARI_T with the Tegen climatology.

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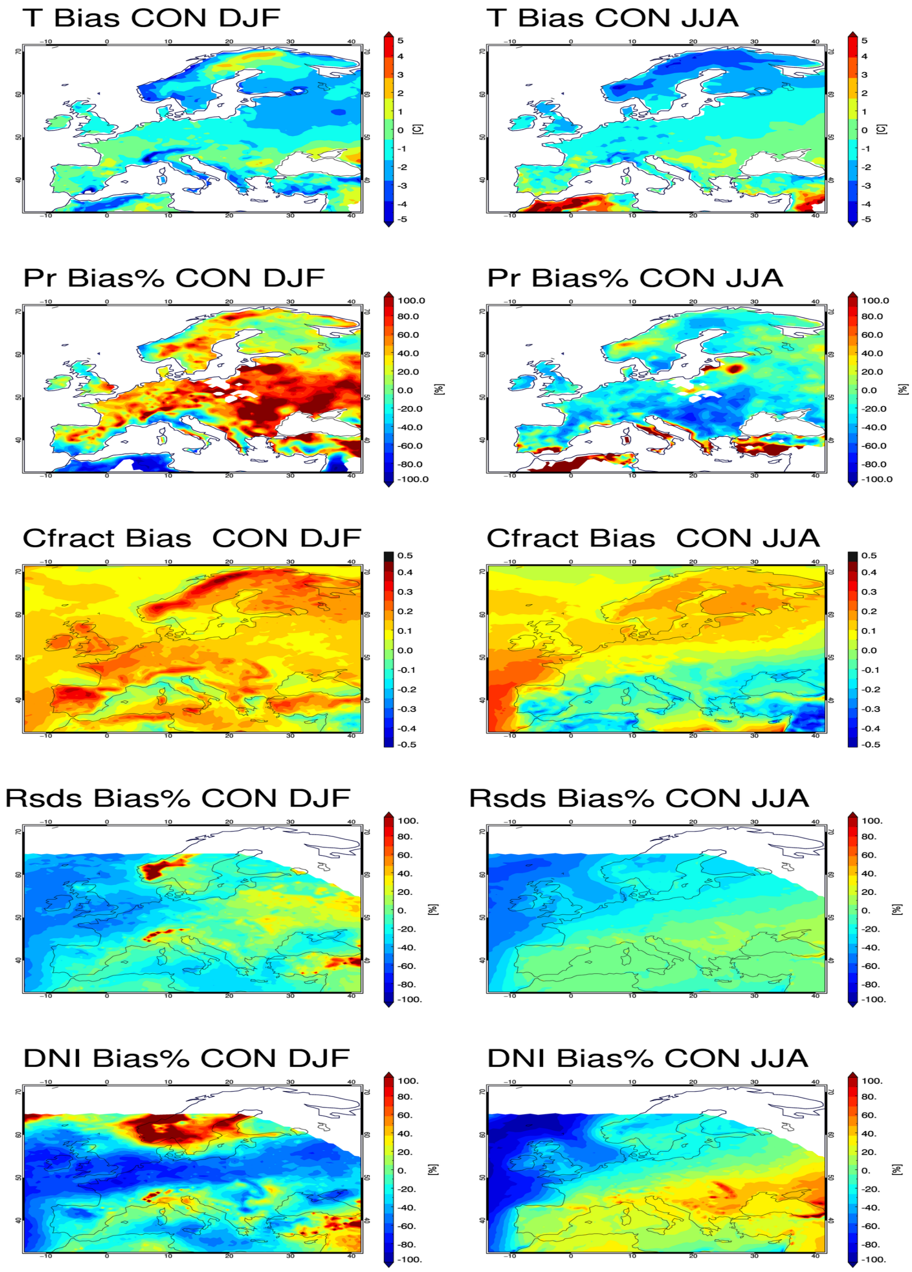

Figure 2. Bias plots for control simulation CON for winter (DJF-left) and summer (JJA-right). Biases depicted from top to bottom for temperature (T), precipitation (Pr), total cloud fraction (Cfract) ,down welling shortwave radiation to the surface (Rsds) and direct normalized irradiance at the surface (DNI).

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3.3 Sensitivities

In this section we explore the impact of the aerosol-radiation and aerosol-cloud interactions implementation on each variable separately.

3.3.1 Temperature

Accounting for the aerosol-radiation interactions only (ARI group) leads to surface cooling (Fig. S2), as expected due to the lower radiation levels reaching the ground. Domain averaged changes compared to CON are negative and generally between -0.1 to -0.3^{o}C with the largest impact seen during summer and autumn (Table 2). These values are very similar to those in the RegCM study over Europe of Zanis et al. (2012). However the study of Nabat et al. (2014) presents a more intense cooling (-0.4 ^{o}C annual average over land). At grid point level impact can be considerably higher, in cases reaching a decrease of 1.5 ^{o}C.

Table 2. Domain averaged temperature difference (^{o}C) compared to CON for all experiments and seasons. Where stated, for simulationARCI the above quantities are also calculated against ACI (ARCI-ACI) in order to assess the implementation of direct effect in the Thompson aerosol-cloud interacting cloud microphysics.

(^{o}C)	DJF	MAM	JJA	SON
ARI_T	-0,1	-0,1	-0,2	-0,4
ARI_Mv1	-0,1	-0,1	-0,3	-0,2
ARI_Mv1urban	-0,2	-0,1	-0,2	-0,4
ARI_Mv1full	-0,1	-0,3	-0,3	-0,3
ARI_MC	-0,1	0,0	-0,1	-0,2
ARCI-ACI	-0,2	-0,1	-0,2	0,1
ACI	0,1	0,1	0,2	-0,1
ARCI	-0,1	0,0	0,0	0,0

The temperature decrease is not constrained to the surface but is also detected at higher levels, with decreasing intensity at higher altitudes, usually reaching 850hPa. In the case of autumn over the Balkans and the Black Sea a decrease of -0.2^{o}C can be seen almost up to 400hPa.

In summer ARI_Mv1urban is the only simulation from the ARI group that presents a large area of statistically significant warming at the surface, seen in summer over parts of the Alps, the Iberian Peninsula, Italy and the Balkans, coinciding with a decrease in total cloud fraction (CFRACT). This warming can be attributed to the highly absorbing "urban" type aerosols that warm the atmosphere by absorbing solar radiation but also can affect temperature through circulation and cloud cover amount changes (Fig. S3). This temperature increase clearly affects the surface but also reaches higher levels up to 200hPa. The aerosol absorptivity, expressed through the SSA, can have a strong effect on the signal of the temperature changes presented. Warming

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of near surface temperature, including the pattern described above during summer (with slightly smaller warming), has also been described by other studies (Huszar et al., 2012; Zanis, 2009) that implemented much more realistic and less absorbing aerosols compared to ARI_Mv1urban.

Contrary to the ARI group, simulation ACI using the Thompson aerosol-cloud interacting cloud microphysics and accounting for indirect effects only results in a domain averaged temperature increase (0.1 to 0.2^{o}C) compared to CON for all seasons except autumn. When the aerosol-radiation interactions are also enabled in ARCI, temperature decreases compared to ACI by -0.1 to -0.2^{o}C regarding domain averages. This is roughly the same amount of cooling seen when the aerosol radiation interactions are enabled in control CON.

3.3.2 Precipitation

Aerosol related domain averaged changes of precipitation are small in all experiments ($\pm$ 0.08mm/day), at most up to $\pm$ 10% in relative values (Table 3). ARI_Mv1urban again has a more intense impact with a relative decrease of -12% in JJA and MAM (-0.2m/day). All the other ARI experiments have no specific tendency of precipitation change throughout the year. In general winter is the season which is least impacted by aerosol implementations. The study of Nabat et al. (2015) using a coupled atmospheric-ocean model showed a decrease in precipitation over Europe. This decrease was attributed to the aerosol induced cooling of SST that led to decrease latent heat fluxes consequently decreasing atmospheric humidity and cloud cover. Therefore the use of prescribed SST in the current study can be seen as a limitation and could particularly affect precipitation results.

The small domain averages are to an extent a product of sign compensation since the spatial pattern of precipitation differences from control is not homogenous but consists of small areas with increases and decreases scattered around the domain (Fig. S4). Precipitation changes at a grid scale level in several cases can exceed $\pm$ 50% , however this effect can probably be attributed to internal model variability and not to aerosol implementation.

A common area of significant precipitation increase in all experiments is seen over the Black Sea in autumn, where a significant CFRACT increase and cyclonic anomaly in the wind field at 850 and 500hPa is present. This characteristic cyclonic anomaly (Fig. S5) is seen in all ARI group simulations but also to a lesser extent in simulations ACI and ARCI (not shown).

There is no clear spatial correlation between changes in cloud amount and changes in precipitation. Over the Black Sea in autumn increase in precipitation coincided with increase in CFRACT. In another case the extended CFRACT decrease seen in ACI over large part of Central and Northern Europe in summer is accompanied by significant precipitation decrease over a much smaller area over Central Europe.

ARI_Mv1urban exhibits the largest and the spatially most extensive impact on precipitation. During summer and spring large areas of precipitation decrease are seen over Central-Southern Europe and the Balkans coinciding spatially with CFRACT decrease (see section 3.3.6). Clearly, the warming of the mid troposphere (Fig. S3) due to the highly absorbing nature of the aerosols in ARI_Mv1urban stabilizes the atmosphere leading to both precipitation suppression and cloud dissolution.

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Table 3. Domain averaged precipitation difference (mm/day) and relative difference (%) from CON. For all experiments and seasons. Where stated, for simulationARCI the above quantities are also calculated against ACI (ARCI-ACI) in order to assess the implementation of aerosol-radiation interactions in the Thompson aerosol-cloud interacting cloud microphysics.

	DJF		MAM		JJA		SON	
	mm/day	relative %	mm/day	relative %	mm/day	relative %	mm/day	relative %
ARI_T	0,00	0	-0,08	-4	-0,08	0	0,04	3
ARI_Mv1	0,00	1	-0,05	-2	-0,03	4	0,00	0
ARI_Mv1urban	-0,06	-1	-0,24	-11	-0,21	-11	-0,06	-1
ARI_Mv1full	-0,01	0	-0,01	0	0,00	9	0,06	3
ARI_MC	0,01	1	-0,09	-5	-0,03	5	0,02	1
ARCI-ACI	-0,04	-1	0,02	1	-0,03	-4	-0,13	-6
ACI	-0,04	-1	-0,05	-2	0,00	6	0,08	5
ARCI	-0,08	-3	-0,03	-2	-0,04	-3	-0,06	-3

3.3.3 Clear sky radiation at the surface and DRE

Accounting for the aerosol radiation interactions leads to statistically significant reductions in clear sky downwelling shortwave radiation to the surface (Crsds). Crsds decreases by -5 to -8% (domain average), depending on the simulation, during all seasons. Larger reductions of $\sim$ 14 % are found in the ARI_Mv1urban simulation.

Figure 3 shows the DRE at the surface quantified as the difference of netCrsds between the experiment and CON. The domain averaged DRE when aerosol-radiation interactions are enabled is very similar despite the different aerosol datasets, for all ARI simulations being around -4 to -5W/m^2 in winter and -14 to -17W/m^2 in summer (Table 4). ARI_Mv1urban shows twice the reduction than other aerosol treatments due to the considerably more absorbing nature of "urban" type aerosols. When implementing aerosol-radiation interactions in an environment where the indirect effect is also present (ARCI minus ACI) the DRE has also comparable values to the ARI experiments. Spatially the DRE correlates very well with the AOD field of each simulation, with the AOD maxima coinciding with the Crsds minima for each experiment. Correlation coefficients for the ARI group range between -0.8 and -0.98. Interestingly, correlations for the simulation ARCI with aerosol-radiation-cloud interactions are smaller (around -0.7 to -0.8) for most seasons and especially during winter (-0.43). Since the Thompson aerosol-cloud interacting scheme produces an evolving AOD field, using the mean AOD pattern might not be sufficient in a correlation analysis, thus partially explaining the decrease in correlation coefficient described above.

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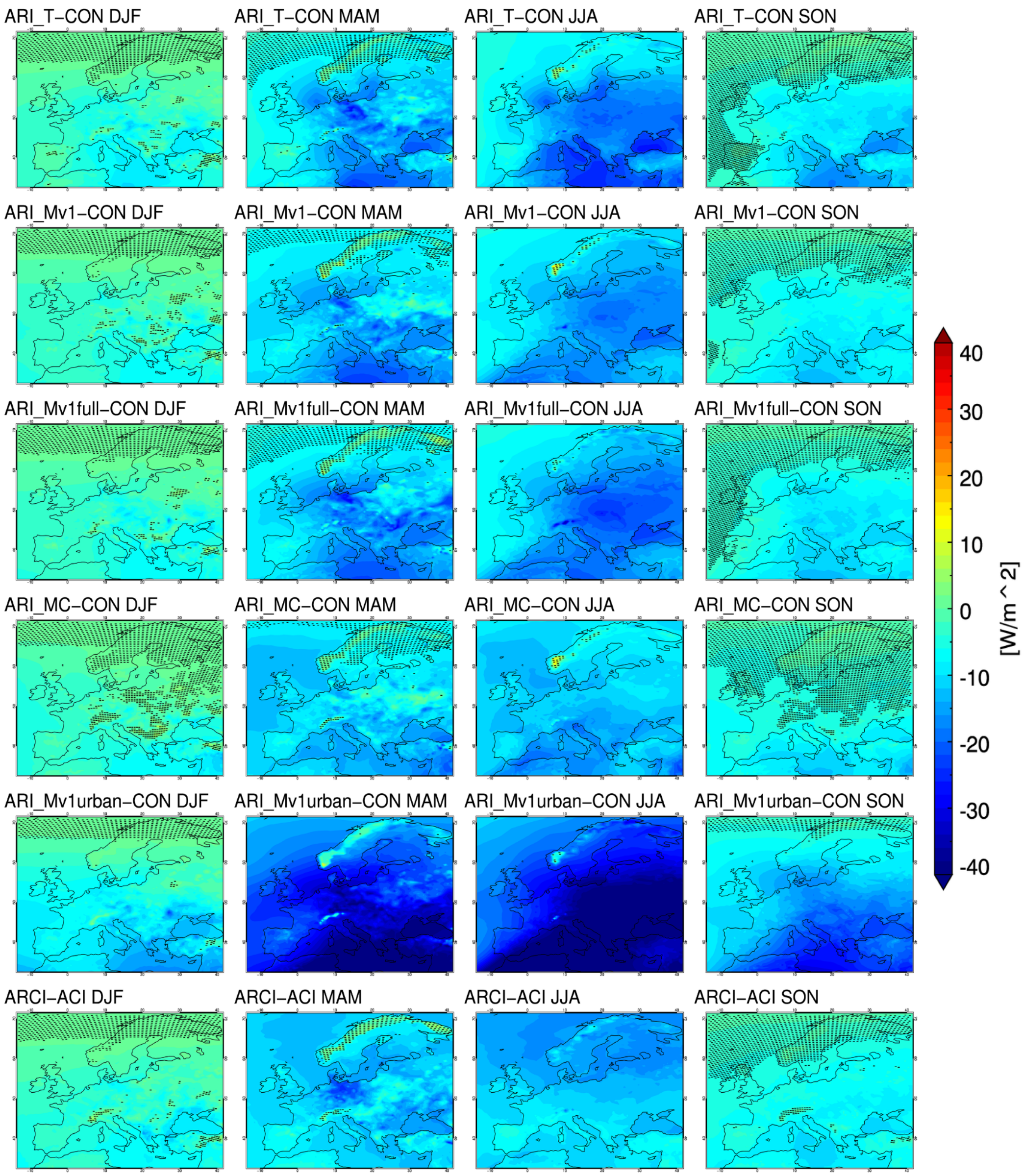

Figure 3. Direct radiative effect (DRE) at the surface for simulations implementing aerosol-radiation interactions for all seasons. DRE has been calculated as the difference in net Crsds at the surface from control CON for the ARI group of simulations (rows 1 to 5). The last row depicts the aerosol-radiation interactions in an environment where the indirect effect is also present and displays the difference of experiment ARCI from ACI. Stippling indicates areas where the differences are not statistically significant at the 95% level, according to the Mann-Whitney non-parametric test.

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3.3.4 Radiation at the surface and RE

For the ARI simulations, shortwave downwelling radiation at the surface (Rsds) shows significant attenuation almost all over the domain throughout the year. Domain averaged Rsds attenuation lies in the range -3 to -8% for all seasons, quite similar with the decrease seen in clear-sky Rsds (Table 5). ARI_Mv1urban is again an exception with higher attenuation around -12 to -16% .

The change in the net shortwave radiation at the surface, constitutes the radiative forcing (RE) of aerosol (Fig. 4) and comprises of the direct radiative forcing (DRE) and the forcing due to changes in cloud amount and properties (ΔSCRE). Accounting of aerosol-radiation interactions only, leads to a negative RE of -2W/m^2 in winter and -11 to -13 W/m^2 in summer (-7W/m^2 annual average) with ARI_Mv1urban roughly doubling these values (Table 4). Compared to other studies our results present in general a smaller radiative effect over Europe. Nabat et al. (2015) showed an annual average RE of -10 W/m^2. The study of Huszar et al. (2012) calculated a similar to our study RE during summer (-12 to -15 W/m^2) but a considerably larger effect (-7 W/m^2) in winter whereas the RegCM3 study of Zanis (2009) for the year 2000 presented a higher summer radiative effect (-16 W/m^2).

The impact of the aerosol-radiation interactions on shortwave radiation weakens when implementing it in an environment where the indirect effect is also present. For example, comparing ARCI with ACI leads to similar behavior as the one from the ARI group, however Rsds attenuation is slightly smaller and RE less negative (-1W/m^2 in DJF, -11W/m^2 in JJA). This is because the change in cloud forcing ΔSCRE (ARCI-ACI) is positive and increased compared to the ARI experiments (eg ACI-CON) (Table 4).

Interestingly, when implementing both the aerosol-radiation interactions and the Thompson aerosol-cloud interacting cloud microphysics with the indirect effect (ARCI) and comparing against the control simulation, domain Rsds averages are increased in the range of 2 to 10% with RE becoming positive, despite the widespread decrease in Crsds. In general, simulations using the Thompson aerosol-cloud interacting scheme, including ACI, present slightly larger positive cloud forcing at the surface, partially attributed to lower cloud fraction values compared to control (section 3.3.6), which leads to an extended Rsds increase and positive RE. As a consequence, ACI that implements the indirect effect only shows domain averaged Rsds increase. In ARCI the domain averaged RE compared to control is almost zero due to the compensation between the negative DRE (direct effect), and positive ΔSCRE. RE includes both positive and negative values, with the positive ones being more intense in the northern and western part of the domain during summer and spring (Fig. 4).

When implementing aerosol-radiation interactions only, the spatial correlation between radiative forcing RE (calculated as a difference from CON) and the AOD field is high (-0.6 to -0.9) and considerably decreases when the indirect effect is included (-0.2 to -0.4). This is due to the cloud fraction changes, attributed not only to aerosol effects but also to the different cloud microphysics scheme used (TE2014).

It is important to note that aerosol optical properties besides AOD can have a severe impact on seasonal radiation amounts. For example, simulations ARI_Mv1, ARI_Mv1full and ARI_Mv1urban all use the MACv1 AOD data but parameterize the other aerosol optical properties differently. ARI_Mv1 and ARI_Mv1full have similar single scattering albedo (SSA) values

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(0.92 to 0.98) which leads to similar results in domain averaged Rsds decrease. Aer2urban however has considerably more absorbing aerosols (SSA starting from 0.6) leading to an almost doubled impact on Rsds attenuation. This impact is widespread over the domain with the overall distribution of Rsds decrease being clearly shifted towards more negative values (Fig. S6). Alexandri et al. (2015) also stressed the importance of secondary aerosol parameters such as SSA in simulating solar radiation in regional climate simulations.

Table 4. Domain averages for each season regarding Radiative effect (RE), direct radiative effect (DRE) and change in shortwave cloud effect at the surface (ΔSCRE) all calculated as differences from control CON. For all experiments. At the first column the aerosol effect that is being implemented is stated above each group of simulations. For simulation ARCI all the above quantities are also calculated against ACI (eg. ARCI-ACI) in order to assess the implementation of aerosol-radiation interactions in the Thompson aerosol-cloud interacting cloud microphysics.

	RE				DRE				ΔSCRE			
Radiation interacting	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
ARI_T	-2	-7	-13	-7	-5	-13	-16	-9	3	7	4	2
ARI_Mv1	-2	-8	-12	-5	-4	-13	-15	-8	3	5	4	3
ARI_Mv1urban	-4	-18	-26	-12	-8	-29	-34	-16	4	11	8	4
ARI_Mv1full	-2	-8	-13	-5	-5	-14	-17	-9	3	6	4	4
ARI_MC	-2	-6	-11	-5	-4	-12	-14	-7	2	6	3	2
ARCI-ACI	-1	-6	-11	-3	-5	-13	-14	-8	4	7	4	5
Cloud interacting + cloud microphysics												
ACI	2	7	10	3	0	0	0	0	2	6	10	3
Radiation + Cloud interacting + cloud microphysics												
ARCI	1	0	-1	0	-5	-13	-14	-8	6	13	13	8

3.3.5 Direct and Diffuse radiation

The ARI group of experiments attenuate the direct normalized irradiance (DNI) more severely than Rsds. Compared to control, domain averaged differences are around -30% for all seasons (Table 5). At grid scale level attenuation can exceed -50% (Fig. S6) especially during winter and autumn where DNI levels are low due to large cloud amounts and small overall radiation levels. When accounting for aerosol-radiation interactions in an environment with aerosol-cloud interactions (ARCI –ACI) the reduction of DNI is smaller (-20% in all seasons). Accounting for aerosol-radiation-cloud interactions (ARCI), further reduces the DNI decrease (-15% in all seasons). In this case, the decrease in DNI due to aerosol-radiation interactions is counteracted

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by the lesser cloud amount of experiments using the Thompson aerosol-cloud interacting scheme. ACI (indirect only) shows small but consistent (75% of all grid cells, Fig. S4) DNI increases (6 to 11% on domain average), due to the decreased cloud cover. Thus the change of only the cloud microphysics scheme can lead to an extensive and considerable impact on direct normalized irradiance.

Diffuse radiation at the surface (DIF) is consistently increased in all simulations with the exception of ARI_Mv1urban (Table 5). The amount increases varies considerably with seasons. For winter it is around 7 to 20% and for summer it is around 30 to 40% . The impact of aerosols in winter is generally more pronounced over areas with low cloud amounts such as southern Europe during summer.

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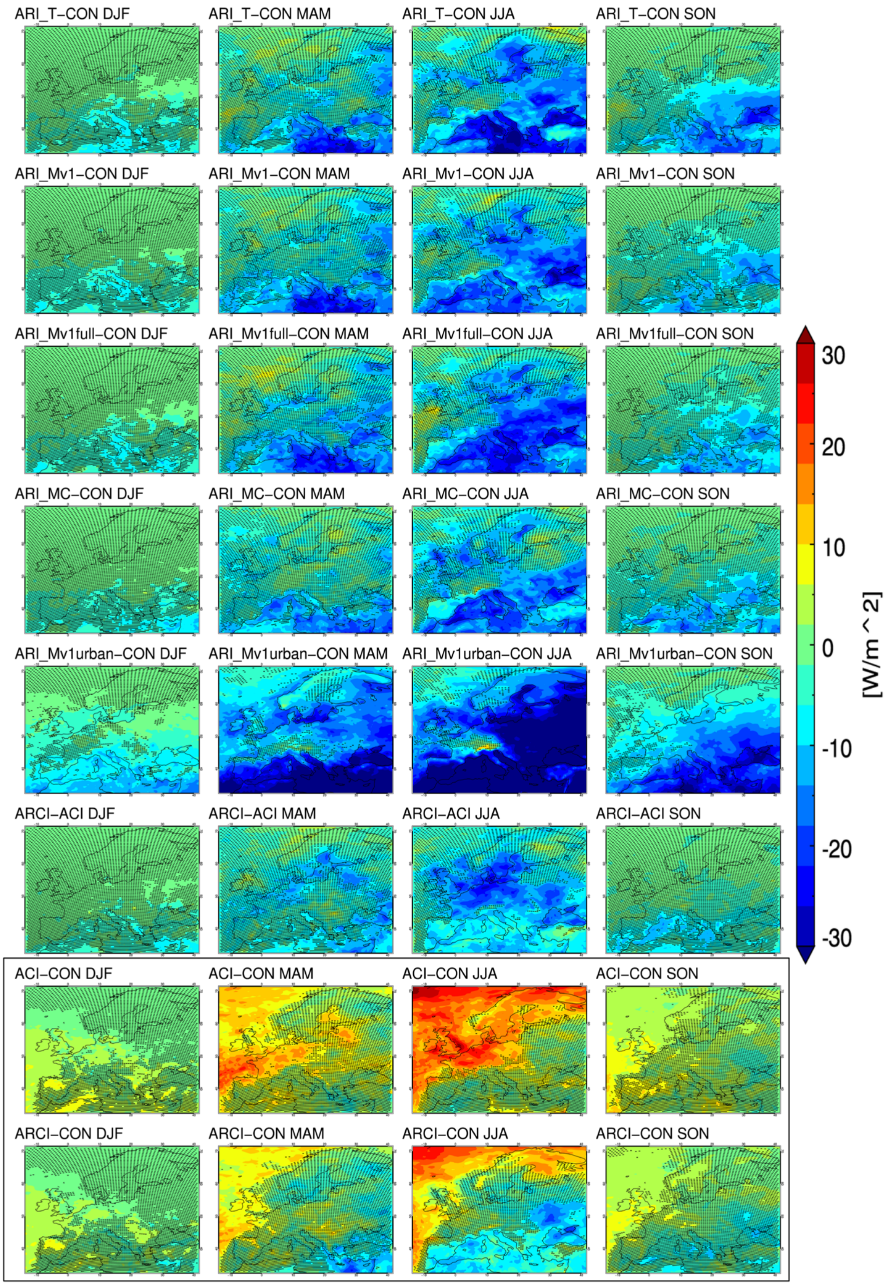

Figure 4. Radiative forcing (RE)calculated against control CON for all experiments and seasons. Furthermore, the RE of ARCI calculated against ACI (ARCI-ACI) is given to assess aerosol-radiation interaction implementation in the Thompson aerosol-cloud interacting cloud microphysics (TE2014) (row six). First six rows present the impact of direct effect. Last two rows(black box) present the impact of TE2014 with indirect effect against control (row seven) and TE2014 with aerosol-radiation interaction enabled against control (row eight). Stippling indicates areas where the differences are not statistically significant at the 95% level, according to the Mann-Whitney non-parametric test.

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Table 5. Relative difference (%) from control CON for shortwave radiation (Rsds), direct normalized irradiance (DNI) and diffuse radiation at the surface (DIF). For all simulations and seasons.

	DJF			MAM			JJA			SON		
	Rsds	DNI	DIF	Rsds	DNI	DIF	Rsds	DNI	DIF	Rsds	DNI	DIF
ARI_T	-5	-30	7	-4	-22	12	-7	-27	36	-8	-31	16
ARI_Mv1	-5	-33	8	-5	-29	17	-6	-30	38	-7	-34	18
ARI_Mv1urban	-11	-33	-3	-12	-29	0	-13	-29	12	-16	-37	1
ARI_Mv1full	-4	-31	9	-5	-28	17	-7	-29	37	-6	-33	18
ARI_MC	-3	-26	7	-5	-27	15	-6	-29	35	-7	-29	15
ARCI-ACI	-2	-20	6	-4	-23	12	-6	-25	26	-3	-18	14
ACI	7	8	7	7	9	5	9	11	6	8	6	7
ARCI	5	-14	13	2	-16	17	2	-17	31	5	-14	21

3.3.6 Cloud fraction and forcing

a) Total cloud fraction

Changes in total cloud fraction (CFRACT) compared to CON due to aerosol implementation are shown in Fig. 5. In general, regardless of the type of aerosol implementation changes are quite small. Therefore, domain averaged differences from CON do not exceed ± 0.01, (scale of 0 to 1). This partially happens because cloudiness increases and decreases in parts of the domain. However, the absolute differences from CON are still quite small with a range of 0.01 to 0.03. Smallest impacts are seen in winter where cloudiness is mainly affected by synoptic phenomena. In relative values domain changes are around 1-2% for winter and up to 3-4% (6% for ARI_Mv1urban) during summer. In ARI_Mv1urban CFRACT changes exceed in some cases 0.15. The aerosol-radiation interactions has a minor impact on CFRACT. The two simulations using the aerosol-cloud interacting cloud microphysics have lower cloud fraction amounts throughout the year compared to all other simulations using the Thompson2008 scheme. This is probably connected to the fact that the above two simulations also present smaller liquid water path (LWP) values.

Some areas show statistically significant differences in CFRACT which follow the pattern of temperature changes. Cloud fraction increase occurs in areas with temperature decrease whereas decreases in cloud cover are related to areas with atmospheric warming. The most pronounced CFRACT increases occur above the Black Sea and eastern Balkans in autumn (including parts of North Africa and Central-Eastern Mediterranean in some cases). These changes are present in all the simulations (Fig. 5). They are probably related to the previously mentioned cyclonic anomaly in the wind field (both 850 and 500hPa) over the Black Sea region (Fig. S5). The introduction of aerosol-radiation interactions reduces radiation at the surface, thus decreasing temperature. This in turn leads to the formation of a cyclonic anomaly that produces larger cloud fraction amounts which in turn further decreases radiation levels hence decreasing temperature, leading to a feedback mechanism. Temperature

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at the surface (around -1°C) is clearly decreased due to the combined effect of aerosols and increased cloud amount. Negative temperature changes extend to higher levels (-0.6°C at 850hPa and -0.2°C at 400hPa). A composite plot showing the ARI_T case using the Tegen climatology is presented in the supplement (Fig. S8).

The impact on cloudiness is more pronounced in ARI_Mv1urban as a result of extreme absorbing aerosols. Significant changes in CFRACT are found in extended parts of the domain for all seasons except winter. This highlights the importance of introducing aerosol optical properties (e.g. SSA) in RCM simulations, as they can affect the thermodynamics of the lower and mid atmosphere (Fig. S3).

The patterns of significant changes in total cloud fraction in our simulations are dominated by changes in low clouds, which are mostly affected (Fig. S9). Medium level cloud changes are less pronounced in amplitude and area extent, whereas higher clouds are least impacted by changes in aerosol treatments. This is to be expected, since our aerosol concentrations are located in the lower part of the troposphere.

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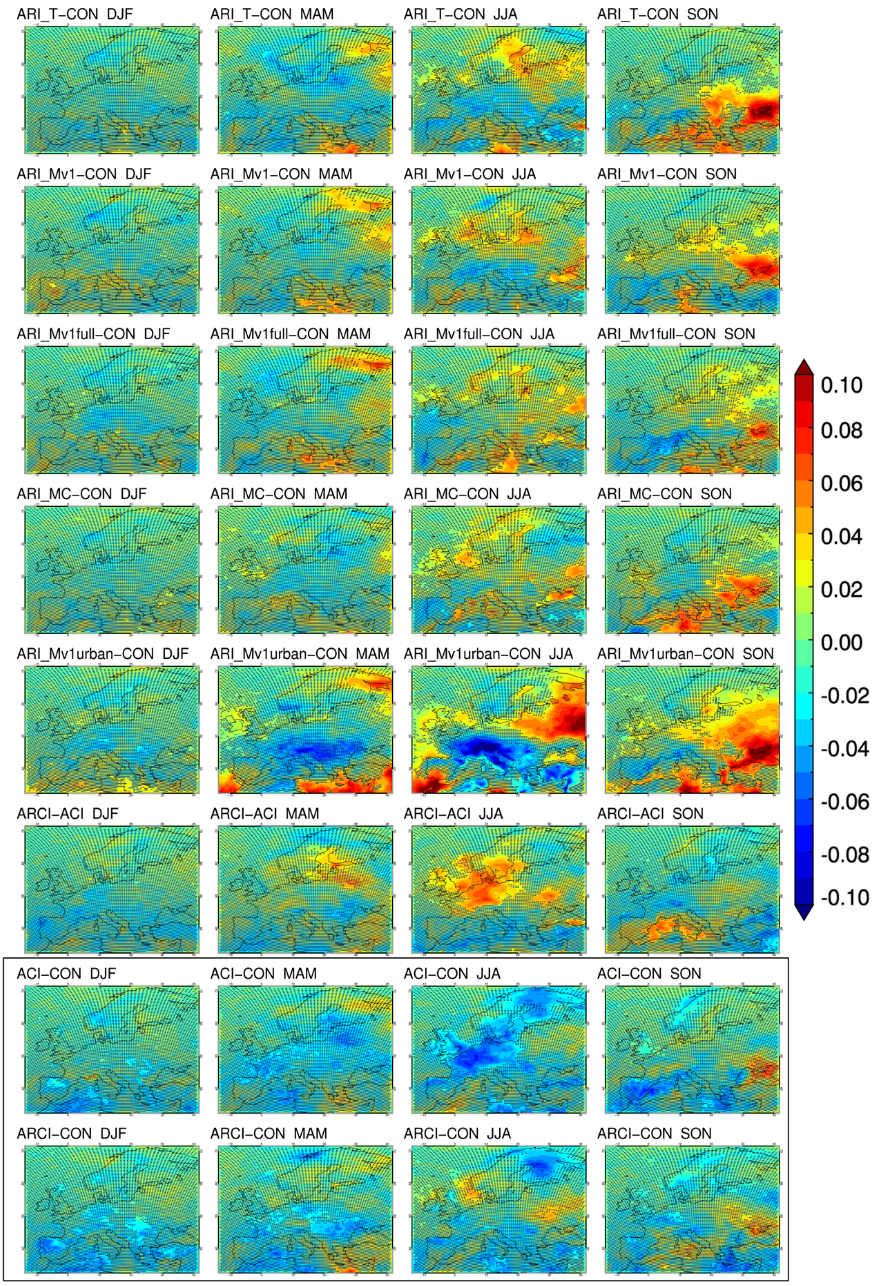

Figure 5. Total cloud fraction (CFRACT) difference from control simulation CON for all experiments and seasons. Furthermore the CFRACT difference of ARCI calculated against ACI (ARCI-ACI) is given to assess aerosol-radiation interaction implementation in the Thompson aerosol-cloud interacting cloud microphysics (TE2014) (row six). First six rows present the impact of aerosol-radiation interactions. Last two rows (black box) present the impact of TE2014 with indirect effect against control (row seven) and TE2014 with aerosol-radiation interactions enabled against control (row eight). Stippling indicates areas where the differences are not statistically significant at the 95% level, according to the Mann-Whitney non-parametric test.

b) Cloud forcing

We showed that accounting for the aerosol-radiation interactions does not systematically change CFRACT, whereas the use of the Thompson aerosol-cloud interacting cloud microphysics lowers the cloudiness. Of particular interest is the impact of aerosol on the ability of clouds to interact with radiation. To study this effect we calculate the aerosol related change in the cloud forcing regarding shortwave radiation at the surface (ΔSCRE) (Fig. 6). The domain averaged change in the cloud forcing is positive in all experiments (Table 4). Thus, the introduction of aerosol-radiation and/or aerosol-cloud interactions leads to more transparent clouds enabling larger amounts of radiation reaching the surface. For ARI simulations ΔSCRE represents the impact of semi-direct aerosol effect on radiation, which is positive with annuals averages around 3 to 4 W/m^2 is largest during spring (5-7 W/m^2). Nabat et al. (2015) had calculated a larger annually averaged semi-direct effect around 5 to 6 W/m^2. This effect is counteracting the direct radiative effect (DRE) of aerosol that is clearly negative. The semi-direct effect accounts for 60% of the direct aerosol effect on radiation (DRE) during winter, 45% during spring and around 20-35% during summer and autumn. Consequently, the impact of semi-direct effect on radiation is considerable, and plays an important role in the overall impact of aerosol-radiation interaction implementation in the model.

When introducing aerosol-radiation interaction in ACI where the indirect effect is also present, the ΔSCRE (ARCI-ACI) represents the combined effect of the semi-direct and indirect effect changes on cloud forcing. In this case ΔSCRE is slightly larger (4-7 W/m^2) compared to the effect in the ARI group, and its relative importance is also increased, amounting up to 80% of the DRE in winter and 65% in autumn.

In ARCI the change in cloud forcing is attributed to the semi-direct and indirect effects as well as the change in the cloud microphysics scheme. In this case the ΔSCRE is further increased to 6 to 13 W/m^2. This results in ΔSCRE being equal in magnitude to the DRE, increasing its relative importance in the overall radiative effect (RE) of aerosol.

The changes in cloud forcing can be attributed to changes in cloud amount but also to cloud properties and characteristics. There are areas with considerable ΔSCRE increase which is accompanied by non-statistical cloudiness change. This behavior is typically seen over the northeastern part of the domain especially over the sea and is more pronounced in the simulations using the TE2014 scheme. In these cases, the positive change in cloud forcing can be attributed to changes in cloud properties that result in decreased cloud optical depth.

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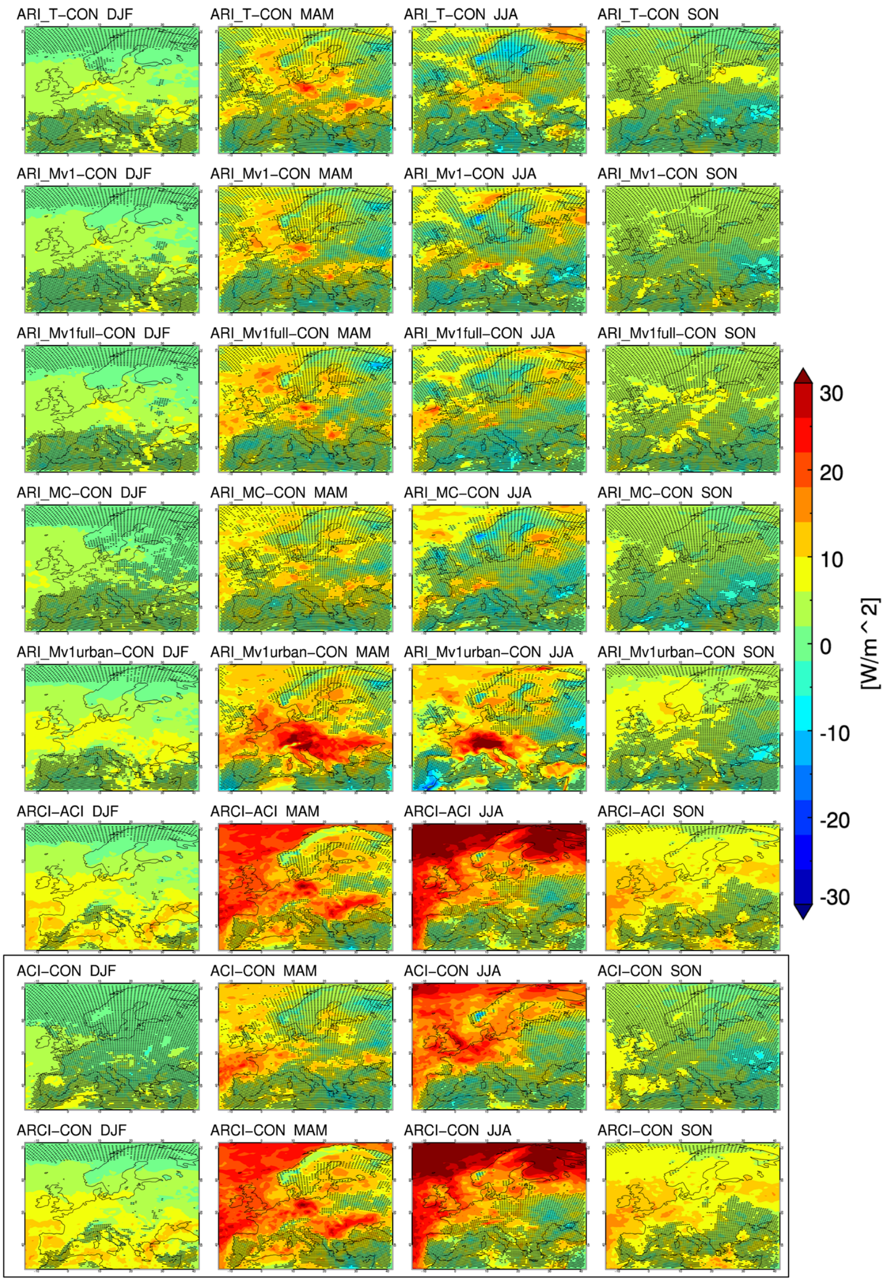

Figure 6. Shortwave cloud radiative effect difference (ΔSCRE) from control simulation CON for all experiments and seasons. Furthermore the SCRE difference of ARCI calculated against ACI (ARCI-ACI) is given to assess aerosol-radiation interaction implementation in the Thompson aerosol-cloud interacting cloud microphysics (TE2014) (row six).The last two rows (black box) present the impact of TE2014 with indirect effect against control (row seven) and TE2014 with aerosol-radiation interactions enabled against control (row eight). Stippling indicates areas where the differences are not statistically significant at the 95% level, according to the Mann-Whitney non-parametric test.

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4 Conclusions

In this study we explore the sensitivity of resolving aerosol interactions within downscaling regional NWP model experiments over Europe using different aerosol products and different modeling options to couple aerosol with model physics accounting for the aerosol-radiation and aerosol-cloud interactions. The aerosol input we tested included older climatologies widely used in climate studies (e.g. Tegen, 1997) and relatively newer products (e.g. ECMWF MACC reanalysis), which have not been extensively tested yet by the RCM community. These new datasets are promising due to their higher spatial and temporal resolution. The different experiments and configurations applied in our model simulations allow for i) the quantification of the direct and semi-direct aerosol effect on European climate and ii) the assessment of the impact of aerosol parameterization (AOD, Angstrom exponent, SSA) and type (absorbing vs non-absorbing) on regional climate.

Our model results show that the aerosol-radiation interactions in the model have a clear and significant impact (-3 to -16%) on shortwave radiation at the surface (Rsds) throughout the year, whereas the influence on direct normalized irradiance (-30%) and diffuse radiation (+10 to +40%) can be considerably stronger. These findings are particularly important for solar applications (e.g., solar power production), since Rsds is often the only available parameter from ensemble climate projects (e.g., CORDEX; e.g. Jerez et al., 2015), although it is neither the most sensitive to aerosol properties nor the most relevant for the impact community (Jimenez et al., 2016).

Accounting for the aerosol-radiation interactions reduces surface radiation by up to -17 (-5) W/m^2 in summer (winter) due to the direct radiative effect (DRE). This reduction is twice as large for aerosol of highly absorbing nature (i.e., urban). Clouds responded (semi-direct effect) with a positive forcing, counteracting the impact of the DRE by 20 to 60% (3 to 4 W/m^2), depending on season. Thus, the overall radiative effect of aerosols (RE) is clearly smaller than the DRE and is approximately -12 (-2) W/m^2 in summer (winter). Similar studies implementing aerosol-radiation interactions have calculated larger values of both overall radiative effect (Nabat et al., 2015; Huszar et al., 2012; Zanis, 2009) and semi-direct effect. Furthermore, when aerosol-radiation interactions are implemented in a simulation where the aerosol-cloud interactions are also introduced, the combined impact of the semi-direct and indirect effects results in an even more positive forcing (4 to 7 W/m^2), thus further weakening the overall aerosol radiative effect (–1 W/m^2 in winter and -11 W/m^2 in summer). We also show that introducing the aerosol-radiation and aerosol-cloud interactions may disturb the climate system in a way that affects cloudiness (especially low-level cloudiness) with the potential to trigger regional circulation anomalies at the lower and the mid-troposphere.

Precipitation was not particularly affected by most of the aerosol perturbations in the 5 year simulations that were conducted. The spatial pattern of changes is patchy and some large local changes are probably a result of internal model variability. This result is in contrast to other regional downscaling studies. The study of Nabat et al. (2015) investigating aerosol-radiation interactions presented precipitation reduction due to the decrease of SST which in turn lead to reduced evaporation and finally reduced cloud fraction and precipitation. That study however used an RCM coupled with a ocean model, which made possible to simulate changes in the SST, a component that our study is missing. In our study, considerable precipitation reduction over extended areas is seen only with the use of highly absorbing aerosols identifying the importance of implementing realistic aerosol optical characteristics, whenever available. Regarding the indirect aerosol effect, the study of Da Silva et al. (2018)

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used the Thompson aerosol-cloud interacting cloud microphysics scheme and showed that increased aerosol loads decreased precipitation amounts. Our study did not experiment with different aerosol loads regarding the indirect effect. Even though the two simulations incorporating aerosol-cloud interactions present reduced liquid water path and cloud fraction amounts compared to the control experiment no significant changes are seen in precipitation amount over the largest part of the domain.

The impact on temperature decreases with height and is detectible up to the 850 hPa pressure level. The idealized experiment with the extremely absorbing "urban" type aerosols leads to tropospheric warming of more than 2^{o}C at the surface affecting the troposphere up to 700 hPa.

Code and data availability. The source code of the Weather Research and Forecasting Model (WRF) is freely available by UCAR/NCAR (http://www2.mmm.ucar.edu/wrf/users/downloads.html). The satellite data used (SARAH Edition1, CLARA-A1) are provided by EUMETSAT through the Satellite Application Facility on Climate Monitoring (CM SAF) (www.cmsaf.eu). The E-OBS gridded data set is provided by ECA&D project (http://www.ecad.eu). The MACv1 aerosol climatology data can be found at ftp://ftp-projects.zmaw.de. The ERA-Interim reanalysis and MACC aerosol data are available by the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://apps.ecmwf.int/datasets/).

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Competing interests. The authors declare that they have no conflict of interest

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