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Sensitivity analysis of the microphysics scheme in WRF-Chem contributions to AQMEII phase 2

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HIGHLIGHTS

- Two WRF-Chem simulations contributed to AQMEII-Ph2 differing in the microphysics.
- Sensitivity of aerosol-radiation feedbacks to the microphysics scheme is analysed.
- Smaller and more numerous cloud droplets are simulated with Morrison scheme.
- Therefore, Morrison scheme is more effective in scattering shortwave radiation.
- Higher liquid water droplet and convective precipitation found in Lin scheme.

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ABSTRACT

The parameterization of cloud microphysics is a crucial part of fully-coupled meteorology-chemistry models, since microphysics governs the formation, growth and dissipation of hydrometeors and also aerosol cloud interactions. The main objective of this study, which is based on two simulations for Europe contributing to Phase 2 of the Air Quality Model Evaluation International Initiative (AQMEII) is to assess the sensitivity of WRF-Chem to the selection of the microphysics scheme. Two one-year simulations including aerosol cloud interactions with identical physical-chemical parameterizations except for the microphysics scheme (Morrison –MORRAT vs Lin –LINES) are compared. The study covers the difference between the simulations for two three-month periods (cold and a warm) during the year 2010, allowing thus a seasonal analysis. Overall, when comparing to observational data, no significant benefits from the selection of the microphysical schemes can be derived from the results. However, these results highlight a marked north-south pattern of differences, as well as a decisive impact of the aerosol pollution on the results. The MORRAT simulation resulted in higher cloud water mixing ratios over remote areas with low CCN concentrations, whereas the LINES simulation yields higher cloud water mixing ratios over the more polluted areas. Regarding the droplet number mixing ratio, the Morrison scheme was found to yield higher values both during winter and summer for nearly the entire model domain. As smaller and more numerous cloud droplets are more effective in scattering shortwave radiation, the downwelling shortwave radiation flux at surface was found to be up to 30 W m^{-2} lower for central Europe for the MORRAT

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simulation as compared to the simulation using the LINES simulation during wintertime. Finally, less convective precipitation is simulated over land with MORRAT during summertime, while no almost difference was found for the winter. On the other hand, non-convective precipitation was up to 4 mm lower during wintertime over Italy and the Balkans for the case of including Lin microphysics as compared to the MORRAT simulation.

1. Introduction

Anthropogenic aerosols exert a substantial influence on Earth's climate, and the current in-terest in studying the atmospheric aerosol has increased due to the need to quantify this influence. Aerosols influence climate by modifying both the global energy balance through absorption and scattering of radiation (direct effects), the reflectance and persistence of clouds and the development and occurrence of precipitation (indirect effects) (Ghan and Schwartz, 2007; Forkel et al., 2012). Aerosols act as cloud condensation nuclei (CCN, first indirect effect), thus affecting cloud albedo and lifetime (Twomey, 1977; Lohmann and Feichter, 2005) and their impacts also include an increase in liquid water content, cloud cover and lifetime of low level clouds and suppression or enhancement of precipitation, which is the second indirect effect (Bangert et al., 2011).

Indirect effects are related to the microphysical processes, which play an important role in how convection develops. Cloud microphysical processes are also very important to predictions of the atmosphere at temporal scales ranging form minutes to centuries, owing to the effects of latent heat release due to the phase changes of water and the interactions between clouds and radiation (Stensrud, 2007).

Several studies have addressed the influence of the aerosols in microphysics. For example, Rosenfeld et al. (2008) studied how aerosol influences precipitation, showing that clouds with lower amounts of CCN rain out more quickly than polluted clouds, which evaporate water before precipitation can occur. Twohy et al. (2005) evaluated the aerosol indirect effect in marine stratocumulus clouds, showing that clouds formed in air with high particle concentrations had higher droplet concentrations, smaller droplet sizes, and lower drizzle rates.

As aerosol is one of the key properties in simulations of the Earth's climate (Kinne et al., 2006; Grell and Baklanov, 2011), fully-coupled meteorology-climate, and chemistry models are required to provide the possibility to account for these feedback mechanisms between simulated aerosol concentrations and meteorological variables in numerical climate and weather prediction models. Within this context, the microphysics parametrization scheme accounts for the processes that govern the formation, growth and dissipation of cloud particles (freezing, sublimation, evaporation, melting and deposition) (Jerez et al., 2013). There are several schemes describing these interactions. Most of these schemes are “single-moment” schemes, meaning that only the total mixing ratio is predicted. “Double-moment” implies additional prediction of number concentrations. If the aerosol effect on microphysical processes and cloud/precipitation evolution is studied, the use of a double-moment scheme will be necessary. The prediction of the number concentration will affect simulated particle sizes and hence gravitational settling, collision/coalescence and cloud radiative properties, and precipitation efficiency (Ghan et al., 1997).

In order to investigate the impact of different cloud microphysics schemes on results of WRF-Chem, two one-year simulations for Europe from the AQMEII (Air Quality Model Evaluation International Initiative) phase 2 modelling exercise are analysed. Both simulations include aerosol cloud interactions for grid scale clouds and differ only by the choice of the cloud physics parameterisation.

In this sense, the main objective of this paper focuses on the following question: Which is the sensitivity of WRF-Chem simulations to the selection of the cloud microphysics schemes? Hence, this work is not focused on characterizing the aerosol radiative effects and feedbacks, which are covered by the study of Forkel et al. (in this issue), Curci et al. (in this issue) or San José et al. (in this issue).

2. Methodology

The WRF-Chem model (Grell et al., 2005) has been used for assessing two different simulations differing only in the microphysics scheme selected. WRF-Chem allows an interactive coupling and simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorology. The model is used for investigation of regional-scale air quality, field program analysis, and cloud–scale interactions between clouds and chemistry. In contrast with the coarse spatial resolution of GCMs, feedback processes over a wide range of spatial scales can be investigated with WRF-Chem. The simulations have been done within the framework of the second phase of the Air Quality Model Evaluation International Initiative (AQMEII) (Alapaty et al., 2012) (http://aqmeii.jrc.ec.europa.eu) which emerged in 2012 and focuses on online-coupled meteorology-chemistry models. Its goal is to assess how well the current generation of coupled regional scale air quality models can simulate the spatio temporal variability in the optical and radiative characteristics of atmospheric aerosols and associated feedbacks among aerosols, radiation, clouds, and precipitation.

The target domain covers Europe for the year 2010. The spatial configuration employed consists of one single domain centered on latitude 50°N, and longitude 12°E. The Lambert Conformal projection has been used according to the project specifications. The vertical model coordinate system consists of 33 vertical sigma levels, the lowest layer height at 24 m and the model top 50 hPa. The horizontal resolution is 23 km and the total number of grid points is 60,750.

The simulations were integrated by continuous runs with 2-days of time slices. The chemistry was restarted form the previous run whereas the meteorology is restarted each time slot. This keeps the simulations consistent with large-scale analysis fields while allowing for the feedback processes to work. The simulation was driven by ECMWF operational analyses (with data at 00 and 12 UTC) and with respective forecasts (at 3/6/9 etc … hours), so that the time interval of meteorological fields used for boundary conditions was 3 h. The chemical initial conditions (IC) were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) IFS-MOZART model, which are available in 3-h time intervals and provided in daily files with 8 times per file.

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2.1. Emissions

The anthropogenic emissions used were provided by the Netherlands Organization for Applied Scientific Research (TNO). The dataset is a follow-on to the widely used TNO-MACC database (Pouliot et al., 2012). The provided species are CH_4, CO, NO_x, SO_x, non-methane VOC, NH_3, PMcoarse, $PM_{2.5}$. A separate PM bulk composition profile file is composed based on the information by source sector by country. The different chemical components represented are EC, OC, SO_2, sodium and other mineral components.

Biogenic emissions were estimated by the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006) which are calculated online. MEGAN is a global model with a base resolution of around 1 km that serves for estimating the net emission of gases and aerosols from terrestrial ecosystems into the atmosphere. Driving variables include landcover, weather, and atmospheric chemical composition.

Fire emissions data were obtained from the IS4FIRE Project (http://is4fires.fmi.fi). The emission dataset is estimated by reanalysis of fire radiative power data obtained by MODIS instrument onboard of Aqua and Terra satellites. The fire assimilation system information is processed into the emission input for the System for Integrated modeLing of Atmospheric coMposition (SILAM) for a subsequent evaluation of the impact of fires on atmospheric composition and air quality. The emission data is available for Europe with $0.1 \times 0.1^{\circ}$ spatial resolution.

2.2. Model configuration

Within all WRF-Chem simulations included in AQMEII Phase 2 (see Forkel et al., in this issue, for further details), the focus of this paper is on two equal simulations differing only in the microphysics scheme. The first simulation (MORRAT) uses the Morrison microphysics scheme (Morrison et al., 2009). The second simulation (LINES) relies on the Lin microphysics scheme (Lin et al., 1983). WRF-Chem configurations used include the following options (Table 1): RADM2 chemical mechanism (Stockwell et al., 1990); MADE/SORGAM aerosol module (Schell et al., 2001) including some aqueous reactions; Fast-J photolysis scheme (Fast et al., 2006); Goddard shortwave radiation parameterization (Chou and Suarez, 1994); Yonsei University scheme (YSU) (Hong and Pan, 1996) for the Planetary Boundary Layer (PBL); dry deposition follows the Wesely resistance approach (Wesely, 1989), while wet deposition is divided into convective wet deposition and grid-scale wet deposition (Easter et al., 2004).

Table 1
Model configuration options.

Option	Name	
Gas phase mechanism	RADM2 (Stockwell et al., 1990)	
Aerosol mechanism	MADE/SORGAM (Schell et al., 2001)	
Organic module	SORGAM (Schell et al., 2001)	
Aerosol size	3 modes (Aitken, accumulation and coarse)	
Planetary boundary Layer	YSU (Hong and Pan, 1996)	
Dust model	MOSAIC MADE/SORGAM (Schell et al., 2001)	
Photolysis option	Fast-J (Fast et al., 2006)	
Microphysic option	Lin (Lin et al., 1983 modified by Chapman et al., 2009)	Morrison (Morrison et al., 2009)
Shortwave radiation	Goddard (Chou and Suarez, 1994)	
Longwave radiation	RRTM (Iacono et al., 2008)	
Prognostic cloud condensation nuclei	Yes	
Direct feedback	Yes	
Indirect feedback	Yes	
Wet deposition	Grid scale wet deposition (Easter et al., 2004)	
Dry deposition	Wesely resistance approach (Wesely, 1989)	

2.3. Microphysic schemes

The Morrison scheme (Morrison et al., 2009) is a double moment scheme including the following six species of water: vapour, cloud droplets, cloud ice, rain, snow and graupel/hail. While single-moment bulk microphysics schemes only predict the mixing ratios of hydrometeors, double-moment methods include an additional prognostic variable that is related to the size distribution, such as number concentration. Prognostic variables include number concentrations and mixing ratios of cloud ice, rain, snow and graupel/hail, cloud droplets and water vapour (total 10 variables). Moreover, several liquid, ice, and mixed-phase processes are included. Particle size distributions are treated using gamma functions, with the associated intercept and slope parameters derived from the predicted mixing ratio and number concentration.

The Lin scheme, based on Lin et al. (1983) and Rutledge and Hobbs (1984), is a single moment scheme including some modifications, as saturation adjustment following Tao et al. (1989) and ice sedimentation, which is related to the sedimentation of small ice crystal (Mitchell et al., 2008). It includes six classes of hydrometeors: water vapour, cloud water, rain, cloud ice, snow, and graupel. This scheme was one of the first to parameterize snow, graupel, and mixed-phase processes (such as the Bergeron process and hail growth by riming) and it has been widely used in numerical weather studies.

According to Li et al. (2008), the one-moment microphysical scheme is unsuitable for assessing the aerosol–clouds interactions as it only predicts the mass of cloud droplets and does not represent the number concentration of cloud droplets. The prediction of two moments provides a more robust treatment of the particle size distributions, which is a key for computing the microphysical process rates and cloud/precipitation evolution. Therefore, prediction of additional moments allows greater flexibility in representing size distributions and hence microphysical process rates.

In this sense, although the Lin microphysic is presented as a single moment scheme, WRF-Chem model allows to transform the single into a double moment scheme. This implementation is described in Chapman et al. (2009). Following Ghan et al. (1997), a prognostic treatment of cloud droplet number was added, which treats water vapour and cloud water, rain, cloud ice, snow, and graupel. The autoconversion of cloud droplets to rain droplets depends on droplet number follows Liu et al. (2005). Droplet-number nucleation and (complete) evaporation rates correspond to the aerosol activation and resuspension rates. Ice nuclei based on predicted particulates are not treated. However, ice clouds are included via the prescribed ice nuclei distribution following the Lin scheme. Finally, the interactions of clouds and incoming solar radiation have been implemented by linking simulated cloud droplet number with the Goddard shortwave radiation scheme, representing the first indirect effect, and with Lin microphysics, which represents the second indirect effect (Skamarock et al., 2005). Therefore, droplet number will affect both the calculated droplet mean radius and cloud optical depth when using Goddard shortwave radiation scheme.

In order to summarize the main differences between the two schemes, cloud droplets spectrum is represented by gamma distribution for Morrison scheme (Morrison et al., 2009) whereas an exponential distribution is used for Lin. All the other hydrometer types are represented by the exponential function in the Morrison scheme.

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3. Results and discussion

3.1. Sensitivity study

The difference between MORRAT and LINES for several WRF variables (such as cloud water mixing ratio, droplet number mixing ratio, 2-m temperature, accumulated cumulus and total grid precipitation and shortwave radiation) is estimated, giving an idea of the sensitivity of the results to the selected microphysics scheme. Mean values for a cold period (January-February-March, JFM) and a warm period (July-August-September, JAS) are considered.

The results of the differences between the two simulations are presented in this section (Figs. 1–4), where MORRAT has been taken as reference. That is, positive (negative) values indicate that

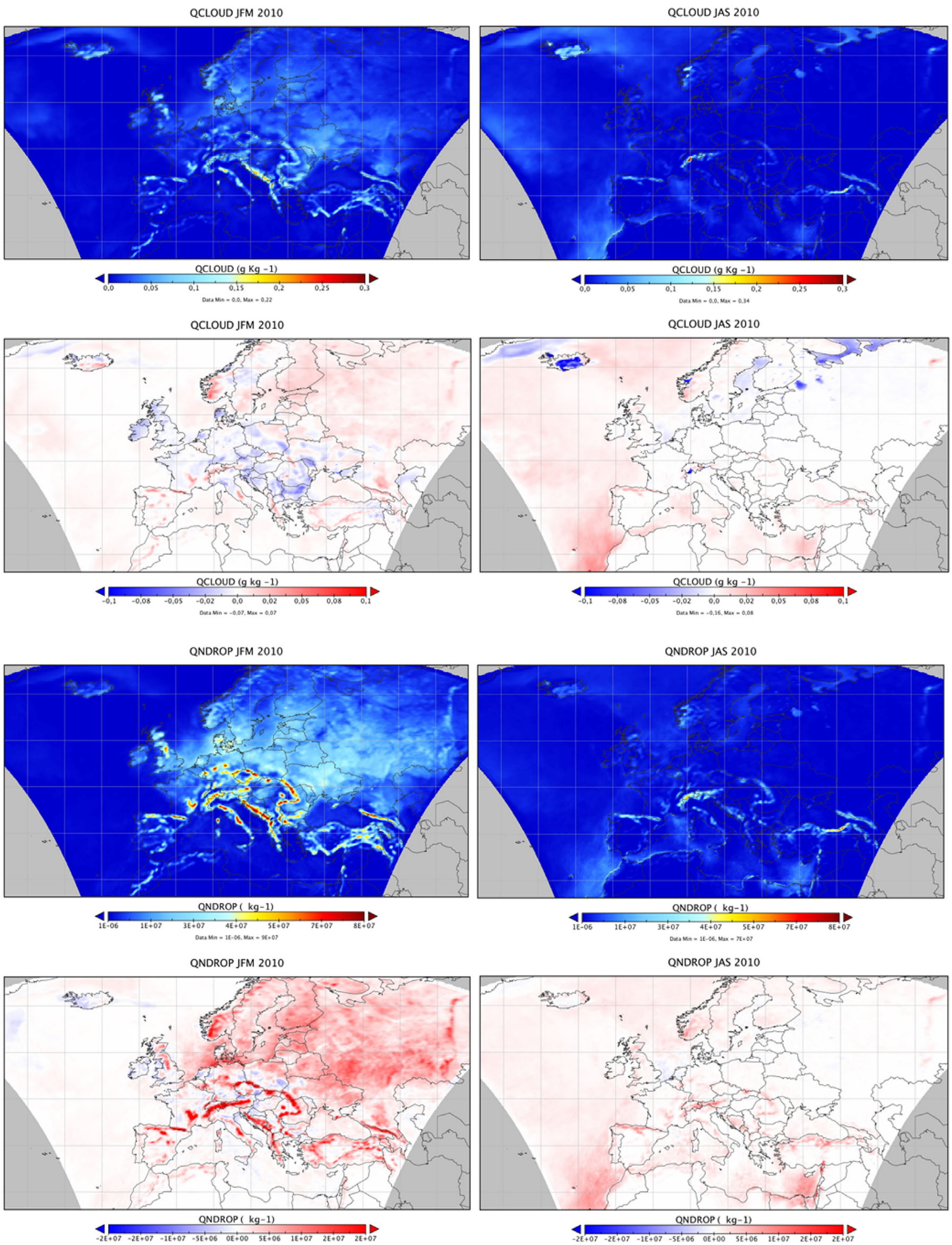

Fig. 1. (Top panel): (First row) Winter 2010 (left) and summer 2010 (right) mean cloud water mixing ratio (QCLOUD) in MORRAT simulations (g kg^{-1}). (Second row) Winter 2010 (left) and summer 2010 (right) mean differences between MORRAT and LINES (g kg^{-1}). (Bottom panel) Id. for droplet number mixing ratio (QNDROP) (kg^{-1}).

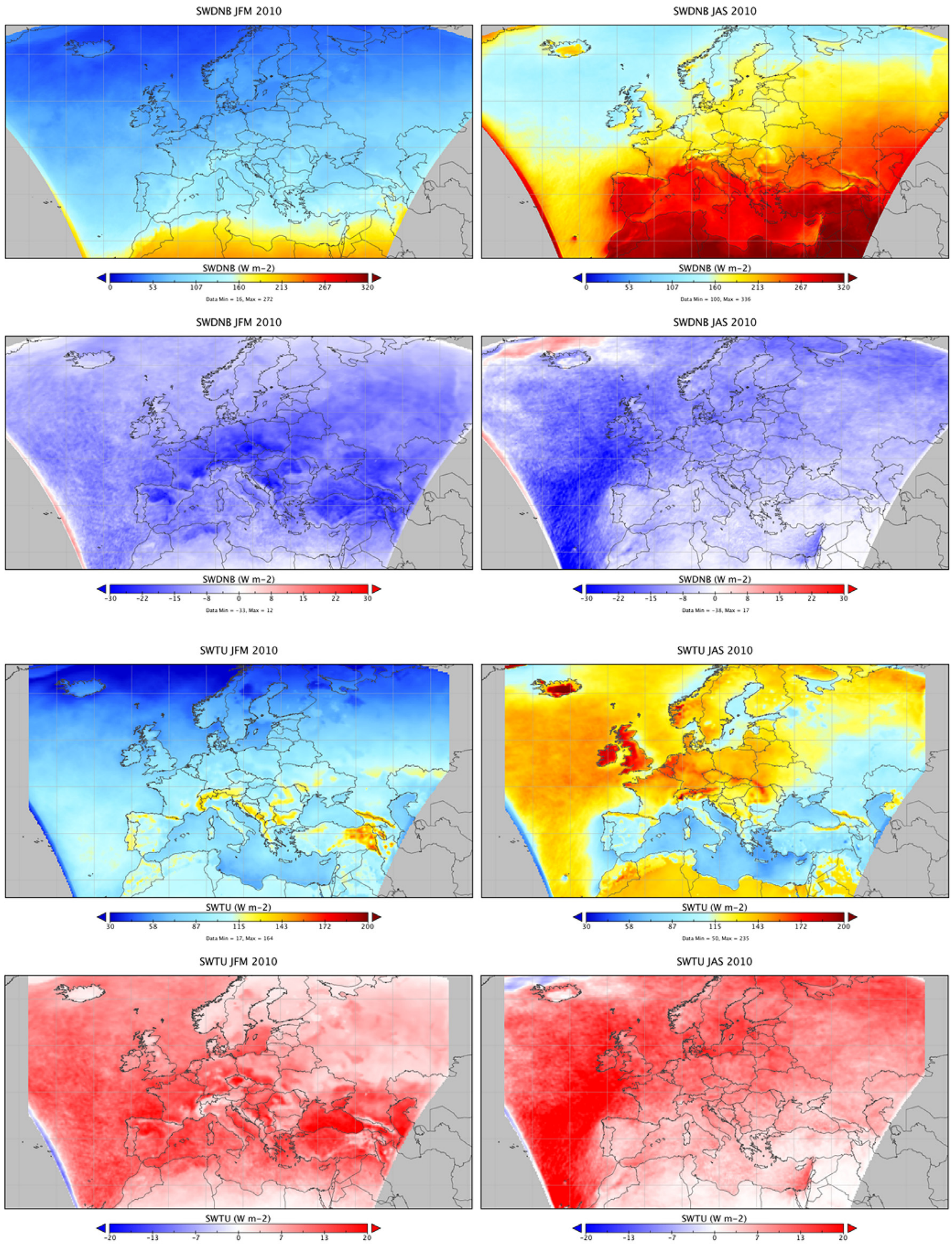

Fig. 2. (Top panel): (First row) Winter 2010 (left) and summer 2010 (right) mean downwelling shortwave flux at bottom (SWDNB) in MORRAT simulations (W m^{-2}). (Second row) Winter 2010 (left) and summer 2010 (right) mean differences between MORRAT and LINES (W m^{-2}). (Bottom panel) Id. for upwelling shortwave flux at the top of the atmosphere (SWTU) (W m^{-2}).

MORRAT simulates higher (lower) levels of the studied variable.

Fig. 1 shows the mean values of cloud water mixing ratio (QCLOUD) and droplet number mixing ratio (QNDROP). MORRAT and LINES simulate similar cloud water mixing ratio for both seasons, with MORRAT providing higher QCLOUD in winter over the northeastern part of the domain, between 60°N to 70°N (+0.05 g kg^{-1}) and remote areas (Mediterranean Sea and Atlantic Ocean; western Scandinavian peninsula; here the differences are up to +0.10 g kg^{-1}) where the CCN concentration is lower. LINES gives higher values of this mixing ratio over central Europe (−0.06 g kg^{-1}) and the British Islands (−0.05 g kg^{-1}). Differences over land are negligible during summertime, but MORRAT

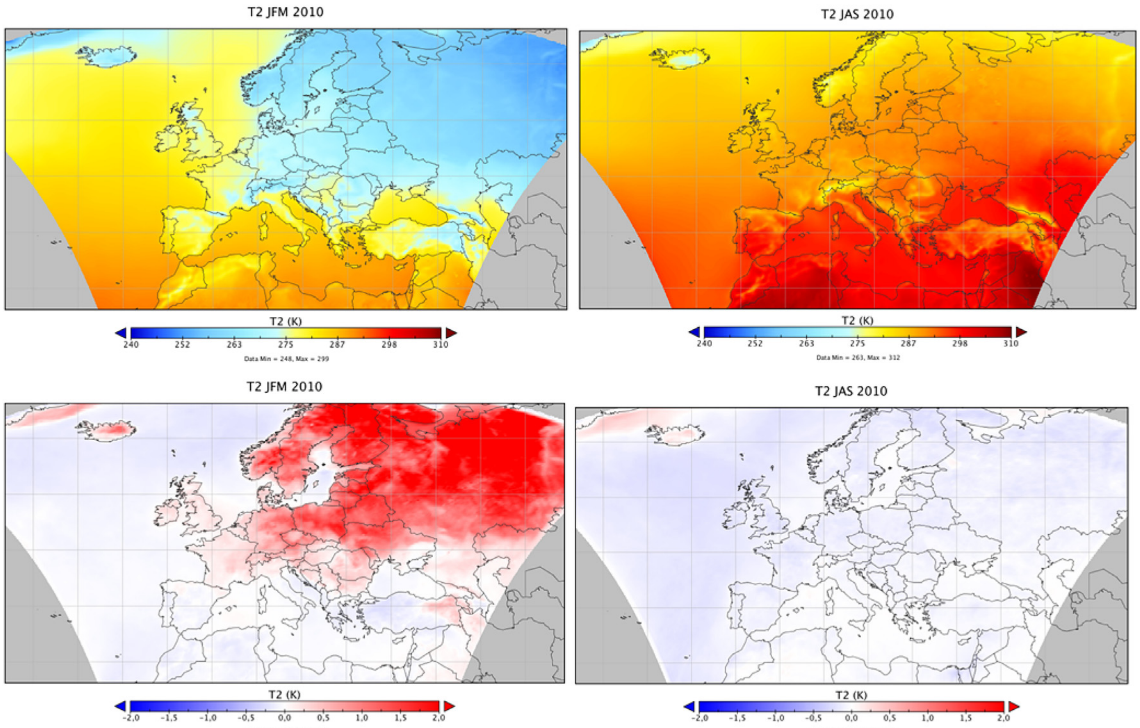

Fig. 3. (First row) Winter 2010 (left) and summer 2010 (right) mean 2-m temperature (T2) in MORRAT simulations (K). (Second row) Winter 2010 (left) and summer 2010 (right) mean differences between MORRAT and LINES (K).

simulates a notably higher QCLOUD (up to +0.08 g kg^{-1}) over the Atlantic Ocean during this part of the year.

Regarding the droplet number mixing ratio, MORRAT simulations indicate higher values of QNDROP both during winter and summer for nearly all the domain of simulation. Highest differences are found for JFM ($+2.5 \cdot 10^7$ kg^{-1}). In summer, QNDROP is more similar between the two runs. As cloud water mixing ratio values are similar for MORRAT and LINES, higher droplet number mixing ratio in MORRAT indicates that cloud droplets have a lower diameter in MORRAT than in LINES, especially during winter. Therefore, smaller and more numerous cloud droplets as simulated in MORRAT should be more effective in scattering shortwave radiation. This is clearly observed in Fig. 2, showing the differences of the mean downwelling shortwave flux at bottom (SWDNB) and upwelling shortwave flux at the top of the atmosphere (SWTU), for JFM and JAS over 2010. According to these variables, MORRAT has lower (higher) levels for SWDNB(SWTU) radiation up to 30 W m^{-2} (20 W m^{-2}) for central Europe during JFM especially during wintertime, reducing to a general MORRAT-LINES difference of −15 W m^{-2} for SWDNB for JAS, with a maximum difference of −20 W m^{-2} in downwelling shortwave radiation at bottom. This fact is conditioned by the higher levels of cloud droplets in MORRAT, leading to a more effective scattering. Conversely, MORRAT-LINES difference for upwelling shortwave radiation at the top of the atmosphere is maximum (+25 W m^{-2}) over the Atlantic Ocean both for JFM and JAS; and minimum (+1 W m^{-2}) in the cold period over north-eastern Europe (Russia, Baltic Countries and Scandinavia).

However, taking a look at 2-m temperature in Fig. 3, higher winter average temperatures are simulated with MORRAT than with the case of including Lin microphysics in the northernmost part of the domain (Nordic countries and Russia, 50°N to 70°N, with differences of +2.5 K). Only small differences are observed for the Mediterranean area and the Atlantic Ocean, where LINES simulates slightly higher temperatures (differences under −0.2 K). The spatial pattern of differences for QNDROP and T2 are highly correlated. MORRAT simulations having higher QNDROP (and therefore, higher levels of cloud droplets) cause lower temperature during the day (as less shortwave radiation reaches the ground), but higher temperature during night (because of more longwave radiation reflected towards the ground, not shown). Between the two effects, the latter prevails, and thus the daily average temperature increases (as observed during wintertime, when QNDROP differences are higher). Furthermore, in winter at these latitudes shortwave heating will be smaller so the longwave effect will be more important. This phenomenon is also described in Forkel et al. (in this issue).

Last, Fig. 4 shows the differences of the accumulated convective precipitation (RAINC) and accumulated total grid scale precipitation (RAINNC). As previously stated in Fig. 1, MORRAT showed higher levels of QNDROP, involving a higher droplet number mixing ratio, but less liquid water droplet. This could be related to the lower convective precipitation simulated over land with MORRAT during summertime (difference up to −1.0 mm over land), while no important differences are found for winter. On the other hand, for non-convective precipitation, highest differences are found over Italy and the Balkans, with negative MORRAT-LINES values up to −4.0 mm (differences are negligible for summertime).

3.2. Numerical model comparison and evaluation

This section is devoted to the evaluation of the two simulations against observations, when available. The reader should bear in mind that the aim of this paper is not to provide a comprehensive model evaluation, which has been already done within the study performed by Im et al. (in this issue-a; in this issue-b) for pollutants and Brunner et al. (in this issue) for meteorology; studies also developed under the umbrella of AQMEII phase 2. However, in order to highlight the differences between the two simulations,

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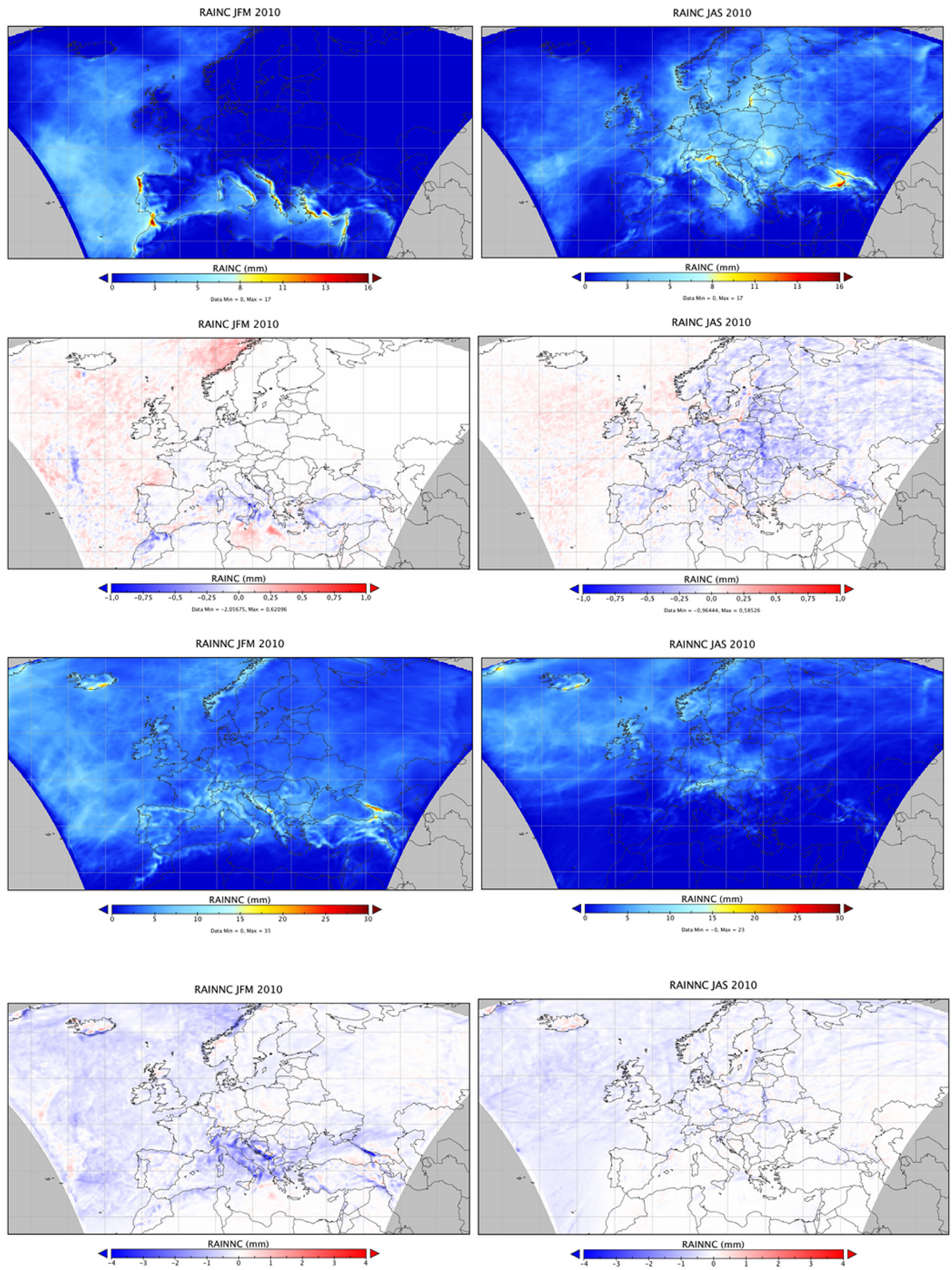

Fig. 4. (Top panel): (First row) Winter 2010 (left) and summer 2010 (right) mean convective precipitation (RAINC) in MORRAT simulations (mm). (Second row) Winter 2010 (left) and summer 2010 (right) mean differences between MORRAT and LINES (mm). (Bottom panel) Id. for grid scale precipitation (RAINNC) (mm).

several variables are evaluated using the web-based platform for model intercomparison and multi-model ensemble analysis ENSEMBLE (http://ensemble2.jrc.ec.europa.eu/public/) hosted at the Joint Research Centre (JRC; Bianconi et al., 2004; Galmarini et al., 2012). Observations include hourly data collected by the AirBase, AERONET and the European Monitoring and Evaluation Programme (EMEP). Several classical statistics are used, such as bias, normalized bias (NB), mean fractional bias (MFB), normalized mean square error (NMSE), root mean square error (RMSE) and the Pearson correlation coefficient (PCC).

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As the results presented in Section 3.1 indicate a marked north-south difference in the patterns (e.g., for T2 or QNDROP), results have been divided into two domains, northern (from 50°N to 70°N) and southern Europe (from 30°N to 50°N), to check whether the models present any spatial-related bias. Table 2 shows the performed statistics over both domains for those variables with observations available within the ENSEMBLE system. Broadly, the sensitivity of the results to the selection of the microphysics scheme is very limited, since the results of the model evaluation are quite similar for both simulations in northern and southern Europe. No significant benefits from the selection of the microphysics schemes can be derived from the results. For instance, both simulations underpredict air pollutants such as SO_2, PM10 and PM2.5 in all domains. The most importance differences are found for tropospheric ozone (O_3) in the southern domain (30°N to 50°N), where the bias is 8.3 $\mu g\ m^{-3}$ for MORRAT and reduces to 2.8 $\mu g\ m^{-3}$ in LINES. However, the differences in the correlation coefficient (PCC) are low for all these pollutants. In this sense, it should be highlighted that the selection of the different microphysics does not seem to improve the time reproducibility of the simulations in both domains.

Table 3 shows the comparison of the statistics for those variables whose observations are not included within ENSEMBLE (observations not available) at receptors taking MORRAT simulation as reference. This has allowed comparing the behaviour of LINES with respect to MORRAT. Hence, LINES minus MORRAT statistics are computed: as an example, a positive bias for a certain variable implies that LINES has a higher value of that variable. The differences for total precipitation are negligible both for northern Europe and southern Europe. The biases are below +0.01 mm, with LINES giving higher precipitation for both domains of study; normalized biases are under +5%, indicating LINES tendency for a higher precipitation. However, a low correlation is observed for both simulations with respect to precipitation (0.52 in northern Europe and 0.62 in southern Europe), indicating a different timing of precipitation in both simulations. Last, shortwave radiation differences are also low (under 15% for both SWUPB and SWDNB), being these variables strongly correlated between the two simulations.

Table 3
Comparison of the two simulations taking MORRAT as reference for those variables not available within ENSEMBLES.

Variable	BIAS[a]	NB[b]	MFB[b]	NMSE[b]	RMSE[a]	PCC
Northern Europe						
PREC	0.0054	0.0381	0.0075	0.6078	0.1119	0.5233
SWUPB	8.2893	0.1536	0.0986	0.1473	22.2506	0.9400
SWDNB	28.8298	0.1108	0.0963	0.0779	76.5125	0.9566
Southern Europe						
PREC	0.0075	0.0457	0.0051	0.4748	0.1152	0.6246
SWUPB	4.9325	0.0636	0.0578	0.0449	16.944	0.9754
SWDNB	21.465	0.0544	0.0566	0.0296	67.852	0.9760

[a] RMSE and BIAS is in units of K for T; $\mu g\ m^{-3}$ for $PM_{2.5}$, PM10 and O_3; ppbV for SO_2, mm for PREC and W m^{-2} for SWUPB and SWDNB.
[b] Parts per unit.

4. Summary and conclusions

Although many aspects related to the microphysics processes are still not completely understood, it is well known that they play an important role in how moist convection develops and evolves, as well as in the radiative energy budget of the Earth-atmosphere system. Therefore, the sensitivity of the selection of the microphysics scheme within WRF-Chem model has been assessed in this contribution. The impact on several variables (such as cloud water mixing ratio, droplet number mixing ratio, shortwave radiation, 2-m temperature, of precipitation) is estimated when selecting two different microphysics parameterizations: Morrison (MORRAT) vs Lin (LINES). Mean values for winter and summer are considered, allowing a seasonal interpretation of the analysis.

MORRAT provides higher cloud water mixing ratio in winter mainly over remote areas, where the CCN concentrations are lower; while LINES gives higher values over most polluted areas. Regarding the droplet number mixing ratio, MORRAT simulations indicate higher values of this variable both during winter and summer for nearly all the domain of simulation. This fact indicates that smaller and more numerous cloud droplets are simulated with the Morrison parameterization, and therefore this scheme is more effective in scattering shortwave radiation (as clearly observed when assessing both the differences in the mean upwelling shortwave flux and the downwelling shortwave flux at bottom).

Table 2
Statistical evaluation of MORRAT and LINES simulations against variables with available observations within the ENSEMBLES system.

Variable	Simulation	BIAS[a]	NB[b]	MFB[b]	NMSE[b]	RMSE[a]	PCC
Northern Europe							
TEMP	MORRAT	−0.4557	−0.0016	0.0051	0.0001	2.8577	0.9582
	LINES	−0.5845	−0.0021	−0.0014	0.0001	3.0333	0.9553
$PM_{2.5}$	MORRAT	−5.9173	−0.4190	−0.3183	2.2049	15.9850	0.3044
	LINES	−6.7524	−0.4783	−0.3889	2.6480	16.5949	0.2406
O_3	MORRAT	−7.4301	−0.1235	−0.0641	0.1809	23.9560	0.6011
	LINES	−10.873	−0.1807	−0.1053	0.2158	25.2972	0.5975
SO_2	MORRAT	−2.7626	−0.5598	−0.6135	4.4752	6.9260	0.4979
	LINES	−2.8481	−0.5951	−0.6981	4.9115	6.9625	0.5078
PM10	MORRAT	−7.7279	−0.3826	−0.2763	0.5053	22.9020	0.1940
	LINES	−8.9224	−0.4417	−0.3450	0.5511	23.5194	0.1518
Southern Europe							
TEMP	MORRAT	−0.8091	−0.0028	−0.0018	0.0001	3.1894	0.9374
	LINES	−0.7816	−0.0027	−0.0018	0.0001	3.1850	0.9379
$PM_{2.5}$	MORRAT	−3.5182	−0.3184	−0.3184	0.9605	8.9402	0.3782
	LINES	−4.0872	−0.3699	−0.3768	1.0789	9.1112	0.3733
O_3	MORRAT	8.2815	0.1332	0.1185	0.1632	26.7421	0.5432
	LINES	2.7612	0.0444	0.0709	0.2416	25.3991	0.5467
SO_2	MORRAT	−4.4496	−0.6080	−0.5337	25.9405	23.3353	0.2005
	LINES	−5.1143	−0.6984	−0.6916	34.1846	23.5168	0.1939
PM10	MORRAT	−21.931	−0.5915	−0.5556	3.4689	44.1400	0.2807
	LINES	−22.883	−0.6172	−0.6061	3.7784	44.5957	0.2818

[a] RMSE and BIAS is in units of K for T; $\mu g\ m^{-3}$ for $PM_{2.5}$, PM10 and O_3; ppbV for SO_2, mm for PREC and W m^{-2} for SWUPB and SWDNB.
[b] Parts per unit.

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It is worth nothing that the spatial pattern of differences for the droplet number mixing ratio and 2-m temperature are highly correlated for wintertime. MORRAT simulations having higher levels of cloud droplets allow less shortwave radiation to reach the ground, but also higher longwave radiation to be reflected towards the ground. Between the two effects, the latter prevails, and thus the daily average temperature increases in northern areas (50°N to 70°N) in MORRAT with respect to LINES.

Despite the differences found in the behaviour of both simulations, the sensitivity of the results to the selection of the microphysics scheme is very limited when comparing the results to observations. No significant benefits from the selection of the microphysics schemes can be derived from the results neither in northernmost areas nor in southern-Mediterranean Europe.

Because of the limitations in this sensitivity analysis (which is restricted to just two simulations implemented in just one model), future research on this topic should be devoted to further studies that examine the impact of aerosols on cloud properties using other microphysics and convective parameterizations, also in other target domains. In this sense, further analysis of the simulations included in phase 2 of the AQMEII initiative could help deepen the study of these processes.

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