

Reviewer Comments:1

Major Revisions:

The authors present two extensions to the regional atmosphere aerosol chemistry model COSMO-MUSCAT. As a first extension, the authors now use the two-moment scheme from COSMO (Seifert and Beheng). The cloud condensation nuclei (CCN) information needed by this scheme comes from MUSCAT (instead of constant, prescribed CCN profiles), following Boucher and Lohmann 1995 and taking sulfate mass as a CCN proxy. The second extension concerns the cloud optical depth in the radiation scheme, which now accounts for droplet-size, via the cloud effective radius, following Martin et al. 1994.

To evaluate the effect of the two new features on code performance, the authors consider a ten day test period (February 15 to 25, 2007). Of this period they focus, however, mostly on one single day (February 17). The simulations are run in forecast mode, thus are not nudged. Variables considered for the evaluation are different cloud related quantities (cover, optical thickness, effective radius, water path, droplet number concentration) and shortwave and longwave net radiation at the surface and the top of atmosphere (TOA). Comparison is done among different model versions (COSMO2M, COSMO2M.rad, COSMO-MUSCAT) and with satellite data (CERES, MODIS, ISCCP) and typically comes in the form of maps.

The authors find significantly improved performance of the new code version when comparing modeled and satellite based cloud effective radius and cloud droplet number concentration. Improvements are less pronounced for other quantities like cloud optical depth, cloud water content, or cloud fraction.

The topic - effect of more elaborated aerosol-cloud treatment in a regional climate model - is of interest. A number of corresponding models exists (e.g. WRF or also COSMO, Zubler et al. 2011), yet given the complexity of the topic a larger number of models whose results can then be compared are clearly desirable. The study thus is of interest.

The study fits the scope of GMD, but requires major revisions to meet GMD standards.

Major Points

1), Precision and / or clarity of statements could generally be improved. Two examples in the following, more can be found under 'minor points' below.

Evaluation is currently done essentially via comparing maps and arguing that things look similar or that there is a slight increase, minor change, a largest change etc. What are the numbers behind such statements? Only few are given. Regional averages, variability, correlations, scatter plots etc. would allow for better quantitative comparison of the different models among themselves and with the satellite data.

What is the resolution (space and time) of the satellite data you use for evaluation? Are model averages based on data from each model time step or based on output data? If output: hourly or less frequent?

ANS: In the revised manuscript a quantitative analysis is included with statistical representation of cloud microphysical properties as probability density functions (PDFs) corresponding to model (COSMO-MUSCAT) and satellite, which can account for different resolution of model and satellite observations (manuscript Figure 5).

In this study we have used MODIS, CERES and ISCCP satellite products for comparisons. The CERES data sets are daily products with spatial resolution of 1°, the given overpass is compared with modeled daily average value. For the case study, ISCCP daily product with spatial resolution 2.5° are used. Further, MODIS level-2 swath data for the time 8.00 to 14.00 UTC are aggregated to model domain (overpass times over the domain). For comparison MODIS products are re-gridded to model domain.

2) You state that you have run the model for 10 days in forecast mode, February 15 to 25, 2007. But you use only one day (February 17) for model evaluation. Why? More importantly, is a one day forecast enough to evaluate the different models? The model may still, above all, be in an adapting stage after only one day (see e.g. Cossu Hocke, GMD, 2014). This may also apply to aerosols, a key element in your study, but with lifetimes on the order of days. While the forecast mode of your simulations makes comparisons more difficult as time evolves, you may still check whether, for example, CCN and cloud optical thickness evolve in concert over the ten days of your simulation. Please comment on possibilities and limitations of your one day forecast comparison. Or re-run your simulations in nudged mode and compare them over a longer time.

ANS: The main objectives are to replace the constant aerosol number concentration in COSMO two-moment scheme with, gridded aerosol information from MUSCAT model and incorporate COSP satellite simulator in the model. For model evaluation we have selected 17 Feb 2007, which is the 3rd day of the simulation, it may reduce the uncertainty in the model prediction as the time progress, also it would get sufficient time for MUSCAT model to evolve the transport processes. In further response to reviewer's remark, additional days were analyzed and compared with satellite observation and they are also in agreement (Figure 1 & 2).

Minor Points:

p.2, l.30-35: As you point out that other groups have already coupled COSMO with two-moment cloud microphysics to an aerosol module, including droplet-size aware radiation. Please explain to the reader how your work differs from these existing, closely related approaches.

ANS: Seifert et al., 2012 has included the cloud-radiation coupling in which effective radii of ice particles and cloud droplets are calculated in the microphysics scheme and passed to the radiation scheme, which is not available with official version of COSMO with 2-moment and has some issues (A. Seifert, personal communication). COSMO-ART is also implemented with double moment scheme, which uses droplet activation based on Bangert et al., (2001), instead of activation rate equation (17) of Seifert et al., (2006).

Section 2.1 I find rather difficult to read as information on different codes (COSMO, COSMO-MUSCAT, and MUSCAT) as well as different code versions (current version, several other versions) is tightly interleaved. It is not always obvious whether what is stated applies to COSMO, COSMO-MUSCAT, the former or present code etc. For example, p.4, l.23ff: to which model do these equations now apply? COSMO2M? If so, how do the CCN numbers given here (1.26×10^9 and 1.0×10^8) go together with the 300 mentioned p.8,l.6? I further guess, but this is not really clear from the text, that equation 7 also applies to COSMO-MUSCAT, but with Cccn taken from MUSCAT and probably k and Smax the same as in COSMO. Please clarify.

ANS: p4, l.23ff: These equations are applied to COSMO model with two-moment, which is revised in the manuscript (COSMO2R). The CCN numbers are applied for continental and maritime conditions (1.26×10^9 and 1.0×10^8), however in this study we have used intermediate aerosol which has a CCN value of 3.0×10^8 , which is also revised in the manuscript.

p.4, eq.3: What is Gamma?

ANS: It is gamma diistribution function.

p.5,l.3: 'aerosol mass concentration information from the MUSCAT model'. Where does MUSCAT get that information from? Are aerosol emissions prescribed? If so, where from? Or concentrations? What are these emissions / concentrations?

ANS: The emission inventory in MUSCAT model is proved by TNO for the Air Quality Model Evaluation International Initiative (AQMEII) project (Pouliot et al., 2012).

In section 3, evaluation against satellite products: is snow cover an issue?

ANS: In satellite retrievals, mainly thin clouds are affected by snow cover, which could be rather ignored.

p.6, l.6: 'with radiation coupled with microphysics': you mean the cloud effective radius following Martin et al. 1994 (your equations 3 to 5) is used? But for a fixed CCN number of 300?

ANS: p.6, l.6: COSMO two-moment with radiation coupled to microphysics (COSMO-2MR), with fixed CCN ($3.0 \times 10^8 \text{m}^{-3}$), which uses equation 3 to 5 in radiation scheme.

p.6,l.27: Unless you have further evidence that for the concrete case ISCCP indeed underestimates cloud cover over the Atlantic, a fairer formulation may be that besides the model having a problem it could also be that the satellite has a problem.

ANS: The problem can arise from both side.

p.7, l.2: 'In the two model versions...' You consider three model versions, COSMO2M, COSMO2M.rad, and COSMO-MUSCAT. While by and by one finds out what two versions you mean here, please state so explicitly.

ANS: Revised as suggested

p.7, l.3ff: Can you comment further on this screening for the liquid phase in MODIS and the models? How dominant is the liquid phase in either one?

ANS: In MODIS satellite retrievals, liquid clouds are screened by setting "Cloud_Phase_Optical_Properties flag=2" and the COSP satellite simulator is able to simulate cloud optical properties for liquid and ice phases separately.

p.7, l.9: 'In both cases it varies between 2 and 50...' Does the real quantity vary in that range or just your colormap? Also, figure 4a shows clearly much more red color than figure 4d. Reducing the comparison of the two panels to their range skips this aspect. In that sense, the patterns are not similar, as claimed in the text. Also, in wide parts where there is substantial cloud optical depth, the satellite based value is about twice as large as the model value. I would not call this a slight difference but a factor of two. This is another example where precision could be improved (major point 1).

ANS: For liquid clouds, we have considered the lower limit of cloud optical depth is 5, which is based on the study by Sourdeval et al., (2015), and the maximum value is 54.0, which are revised in the manuscript. This part is also revised as suggested.

p.7, l.14 ; High values for cloud effective radius are also seen over land. And, as above (p.6, l.27), it is not obvious that the flaw is with the satellite data.

ANS: p.7, l.14 has been removed from the manuscript, and p.6, l.27.: This may either due to the coarse (280 km resolution) resolution of the satellite observation or poor parameterization of clouds in the model.

p.7, l.21: What do you mean by 'largest impact'? Largest in what sense? Change in mean? Median? Percent or absolute? Per grid box?

ANS: p.7 l.21 has been removed from the manuscript.

p.7, l.25: 'slight increase': what is slight?

ANS: p.7, l.25: In the case of cloud optical depth and cloud water path, both generally show an increase despite of reduction in a few areas.

p.7, l.26: 'The cloud optical depth shows a variation in the range of +/-20...' Variation over what? Spatially? Within a model? Please clarify.

ANS: The revised parameterization in coupled model has made modification in spatial distribution of cloud optical depth in the range of ± 15 and the liquid water exhibits a variation in the range of $\pm 0.12 \text{ kgm}^{-2}$.

p.8, l.8: There is a wide region (red in figure 5d) with CCN of at least 300, i.e., the prescribed CCN value in COSMO2M. Yet the CDNC in COSMO-MUSCAT is much lower than in COSMO2M also in this region. Why?

ANS: The sulfate aerosol number concentration in Figure 6d is vertically averaged. The high CCN values are mainly occur below the cloud layers because the high pressure in this region results in trapping CCN below boundary layer.

p.8, l.14: 'While comparing with high resolution MODIS satellite products...' These have not yet been introduced, I think.

ANS: Rephrased to MODIS level-2 products

Section 3.3.: It would be interesting to elaborate a bit more on radiation. For example, the differences between COMSMO2M and COSMO2M.rad seem to be larger over sea than over land. True? Do the large differences (more downward SW and upward LW at the surface especially over sea) go hand in hand with reduced cloud optical thickness? Change in cloud effective radius? Cloud cover? Regarding the comparison with CERES: what area means of CERES and models? Given that you look at February (little radiation, snow cover, short days) and a cloud cover close to 100 percent over wide regions: how reliable are CERES surface fluxes?

ANS: The effect of aerosol-cloud-radiation interaction can be seen to larger extend over ocean than over land, especially for surface net downward short wave and long wave fluxes. The cloud microphysics modification results more surface SW and LW radiation over sea. During winter the uncertainty in the CERES flux is little higher due to large zenith angle (Guo et al. 2007).

p.8, l.30: 'This paper presents an initial approach to the modification of Seifert and Beheng (2006) two-moment scheme in the COSMO model.' This is not true. Other groups have done this before, e.g. Zubler et al. (2011) whom you cite.

ANS: Rephrased to : This paper discusses the modification of Seifert and Beheng (2006) two-moment scheme in the COSMO model.

p.9,l.2: Maybe state that this parameterization takes sulfate mass as a proxy, it is not a full grown aerosol module like SALSA, M7, etc.

ANS: Revised as suggested

p.9, l.8: 'In terms of the cloud distributions, this modification has only a minor effect.' Given that you compare the second day of forecast simulations in winter, this is not truly surprising. To what degree is this finding just due to large scale weather condition or your initialization?

ANS: We do not have another simulation to clarify.

p.9, l.9: What means daily averaged when you consider only one day in the first place?

ANS: In the case study, model results are compared with satellite products. While comparing with ISCCP, the model data is daily averaged because the satellite products are daily products. Whereas in MODIS (Terra) level-2, overpass observations are considered, which is between

8.00 - 14.00 UTC over the domain, so the models outputs are averaged between 8.00 to 14.00 UTC.

p.9, l.10: 'The modified model simulations are in broad agreement with satellite observations.' I would argue that all your simulations are in 'broad agreement'. However, you see some improvements (as you state) in your modified version.

ANS: The interactive treatment of aerosols in COSMO-MUSCAT simulations show an improvement in the cloud microphysical properties. Further, the PDF analysis has contributed to a quantitative comparison of model results with satellite observations.

p.9, l.15: '...only minor changes in terms of the radiation budget were found.' Looking at figure 6, i-l, I would not call these changes minor. In wide regions they are on the order of a factor of two.

ANS: Again, considerable changes ($\approx$ factor of 2) in terms of the radiation budget were also found. The new approach now, however, allows to explicitly take into account the radiative effects of aerosol-cloud interactions.

Figure 1: Why does it say "M7 to be implemented"? In the reference you cite, Wolke et al. 2012, it is stated that M7 is implemented. Please explain. And if M7 does indeed not form part of your model version, remove it from Figure 1.

ANS: In this version of COSMO-MUSCAT(V5.0), M7 is not yet implemented. Also Figure 1 is modified without M7.

Figure 2: What is the data source?

ANS: Initial state of model simulation.

Figure 3: Does cloud cover from COSMO2M, and possibly COSMO2M.rad, look similar to cloud cover from COSMO-MUSCAT?

ANS: The COSMO2M and COSMO2R cloud cover looks similar, however COSMO-MUSCAT cloud cover has been modified due cloud microphysics modification.

Figure 4: While the figure is useful, some more quantitative comparisons would also be useful, e.g. area means, variability, scatter plots... For example, what is the area mean cloud water path in 4i? And how does it compare with the area mean of 4f? Figure 4i looks as if there is above all a change in spatial distribution of the cloud water path, not of total cloud water path (area mean). The same question may be asked for figures 4g and 4h.

ANS: It would be difficult to have a correlation of area mean with satellite observation, because of the different grid points and the satellite products are combined for different swaths. Also the area mean would increase the uncertainty. To overcome this we have compared PDFs of cloud microphysical properties.

Figure 4: How different would the figure be if you were to compare COSMO-MUSCAT with COSMO2M.rad? Put differently, are the differences mainly due to the variable CCN or also to the size-aware radiation?

ANS: There are some difference, if we compare COSMO-MUSCAT with COSMO2MR, however, it can be more clear if we compare COSMO2MR with COSMO2M. It is noticed that the major difference is due to CCN (Figure 3).

Figure 5c: Point out that this is not a MODIS product but a derived quantity. Also, why is there hardly anywhere a CDNC greater than 10? After all, there is cloud cover all over the

place and $CDNC=10$ or smaller is very low.

ANS: CDNC can be derived from MODIS cloud optical depth τ_c and effective radius r_e (Quaas et al., 2009), which is given by,

$$N_d = \alpha \tau_c^{0.5} r_e^{-2.5} \quad (1)$$

where $\alpha = 1.37 \times 10^{-5} \text{m}^{-0.5}$. In the above equation the lower limit of τ_c and r_e are constrained to 5 and 2. This would result in removing lower CDNC values.

Figure 6: On the western boundary of the domain, there seems to be a boundary effect. Can you comment?

ANS: The boundary effect in the difference can be ignored, which arises due to different physics in COSMO and GME.

Figure 6 j-l: Given that the color scale is saturated in wide regions in these plots, why not take it larger? Possibly even -40 to +40, as in 6i?

ANS: Figure 6 and 7 are revised

Figure 7, a-d: Same figures as in figure 6 e-h. No need for duplication. You may consider replacing these panels with corresponding ones from COSMO-MUSCAT, so one has all three models and CERES shown.

ANS: Figure 7 is revised with COSMO-MUSCAT.

Figure 7 6: What time is shown? February 17? 24h mean? Color scale in the SFC SW plots could be reduced to maybe 200 instead of 260 to fully exploit the range of the color table.

ANS: Figure 7 is revised. It is for February 17, 24h mean.

It maybe worthwhile to point out somewhere that you only changed the model but did not (yet) re-tune it, e.g. to get reasonable 2m temperature or precipitation. You show that the different codes give, for example, different cloud optical properties. But this does not imply an overall better model performance.

ANS: Although the two-moment cloud microphysics scheme in COSMO model has been modified, the model did not re-tuned to get reasonable 2m temperature or precipitation. This sentence is included in conclusion section.

The language needs brushing, there are a number of sentences that do not work on the language level. I give only two examples.

ANS: The language has been revised.

p.2, l.6/7: "Although regional models do not describe part of the large scale feedbacks which are included in GCMs, regional modeling allowing for an optimal compromise.

ANS: P.2, l.6/7: Even though regional models do not describe part of the large scale feedbacks, it provides optimal compromise.

p.8, l.8/9: "From figure 5c, the maximum aerosol mass concentration observed over south eastern Europe, on the contrary N_d shows less.

ANS: p.8, l.8/9: From figure 6d, maximum aerosol mass concentration is observed over south eastern Europe. On the contrary, N_d shows less over the same region.

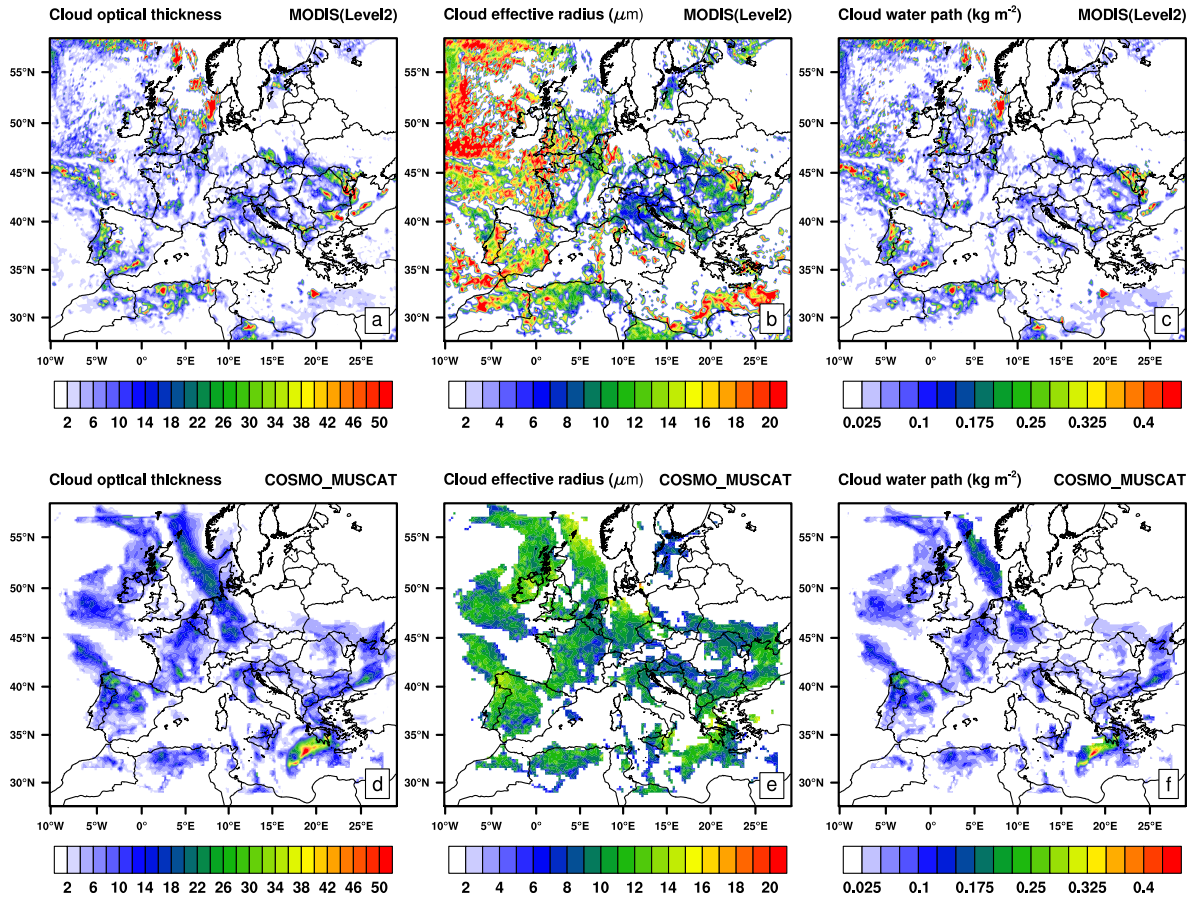


Figure 1: MODIS Level-2 (a) cloud optical depth, (b) cloud effective radius, (c) cloud water path, COSMO-MUSCAT derived (day time averaged) (d) cloud optical depth, (e) cloud effective radius, (f) cloud water path for 23 February 2007.

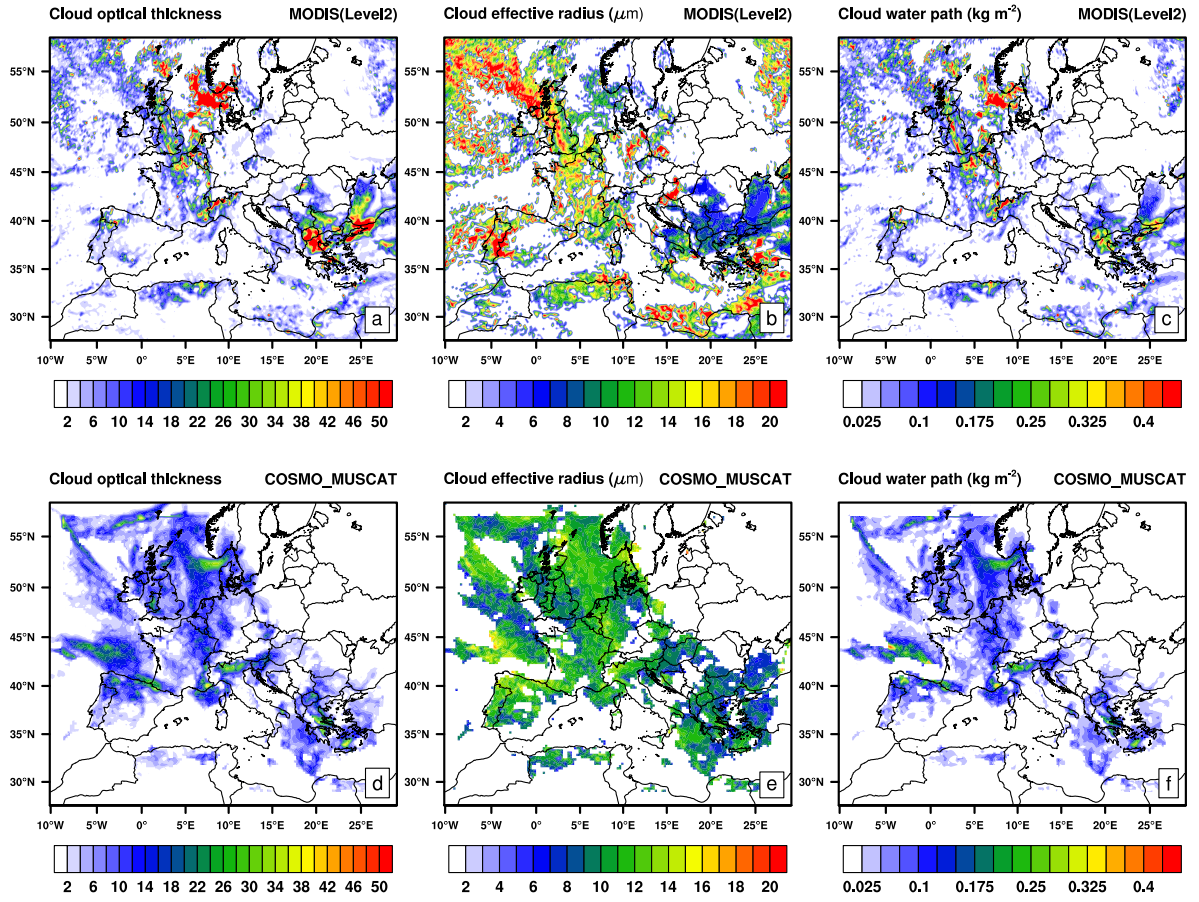


Figure 2: MODIS Level-2 (a) cloud optical depth, (b) cloud effective radius, (c) cloud water path, COSMO-MUSCAT derived (day time averaged) (d) cloud optical depth, (e) cloud effective radius, (f) cloud water path for 24 February 2007.

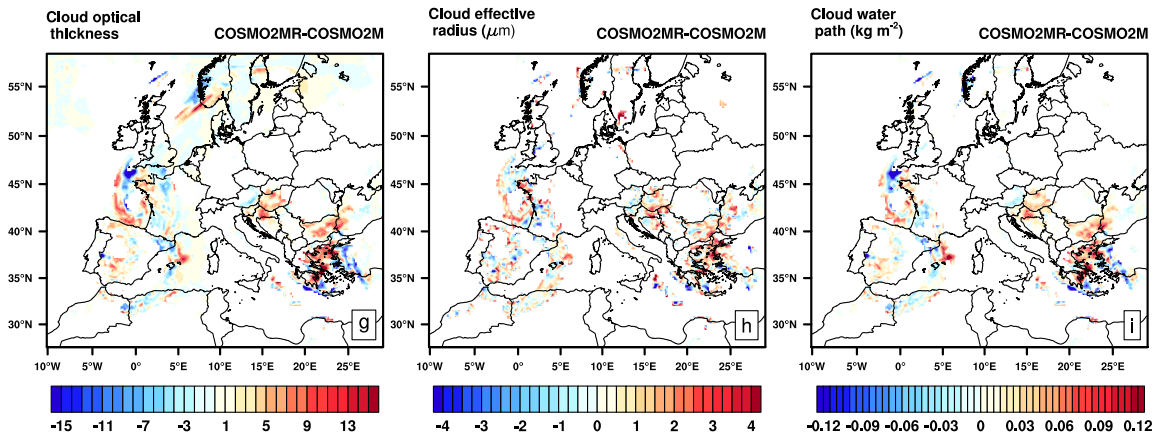


Figure 3: Comparison between COSMO2MR and COSMO2M for 17 February 2007.

Reviewer Comments:2

Major Revisions:

• *Whilst the paper gives a detailed introduction of the general benefits of regional models with online coupled aerosol-cloud, aerosol-radiation and aerosol-cloud-radiation interactions, such as WRF-CHEM (Grell et al. 2005), COSMO-ART (Bangert et al. 2011), COSMO-M7 (Zubler et al. 2011) and COSMO-ART/M7 (chapter 2 of: <http://e-collection.library.ethz.ch/eserv/eth:48845/eth-48845-02.pdf>), I would like to be given further motivation regarding the advantages of their particular approach and have it contrasted to existing approaches.*

My questions raised here, could guide such a discussion:

1) *Why did you use the Boucher and Lohmann's (1995) empirical relation, rather than implementing newer approaches using Koehler theory that have previously been applied in COSMO-ART/COSMO-M7 such as Abdul-Razzak & Gan (2000), or Nenes & Seinfeld (2003)? What is your justification for only considering sulfate and ignoring nitrate contributions to CCN?*

ANS: Our objective is to replace constant C_{ccn} in COSMO model with C_{ccn} from MUSCAT model. This particular version of COSMO-MUSCAT (Version 5.0) is only available with aerosol mass concentration for different aerosol species. As an initial stage of two-moment scheme modification, we have used Boucher and Lohmann parameterization to convert sulfate aerosol mass concentration to C_{ccn} number concentration. In the next step, M7 will be implemented and we could directly use aerosol number concentration in the two-moment scheme, along with new approaches.

2) *Whilst the relationship between cloud optical depth, effective radius and vertically integrated liquid water content is a commonly used diagnostic, it is wavelength independent. How did you deal with this issue when implementing this approach in a radiation scheme that computes the radiative transfer within 3 SW and 5 LW bands covering the entire wavelength spectrum?*

ANS: Even though the cloud optical properties are wavelength independent, the extinction coefficients are calculated from wavelength dependents variables. The extinction, scattering and asymmetry parameters are depends on entire wavelength spectra (Zubler et al., (2011)).

• *Furthermore, a short motivation should be included regarding the chosen case study. Are all the clouds shown boundary layer stratocumulus?*

ANS: A short motivation is included in the manuscript. All clouds are not boundary layer stratocumulus, it consists of convective clouds too.

• *The model evaluation is performed on a single day. The authors argue that the forecast skill decreases with increasing lead time. Could you obtain better agreement and therefore obtain a longer evaluation period if you performed nudged simulations? Otherwise, a brief justification should be given that 1 day is a sufficiently long time period for your evaluation.*

ANS: Even though the model comparison via spatial distribution is performed only for a single day, more quantitative analysis (PDF comparison for single day and for entire simulation) has been carried out and included in the manuscript (Figure 5). The nudged

simulation may improve the evaluation, however in this first stage we are mainly focusing on COSMO-MUSCAT coupling and COSP satellite simulator incorporation and its comparison with observations. A brief justification is included in the manuscript.

General Comments:

- *This paper talks about the coupling of aerosol-cloud interactions and aerosol-cloud-radiation interactions. However, it should be stated clearly (already in the abstract) that these interactions are only included explicitly for warm-phase cloud processes.*

ANS: These interactions are applied for liquid water clouds due to complexity of the aerosol cloud interaction in ice clouds, which is mentioned in the manuscript.

- *The paper often talks about changes to the COSMO model in general. However, the modifications are applied not to the COSMO model in general, but to the COSMO version of COSMO-MUSCAT. Whilst I agree with the authors that CCN variability and aerosol-cloud-radiation coupling is not provided in the officially released code versions, such developments have already been included in other COSMO versions (COSMO-ART, COSMO-M7, COSMO-ART/M7). They are therefore not new to the COSMO code itself.*

ANS: Although, different COSMO versions (COSMO-ART, COSMO-M7, COSMO-ART/M7) have been modified, these models used different cloud microphysics (mainly droplet activation), for example in COSMO-ART the droplet activation based on Bangert et al., (2001), which replaces the activation rate of equation (17) of Seifert et al., (2006) and in COSMO-M7, it is treated with following parameterizations Leaitch et al. (1996), Lin and Leaitch (1997), and Lohmann (2002).

- *The paper is written in good scientific English. However, some sentences require re-writing (some of which are listed below). Furthermore, articles are missing in a few places.*

Specific Comments:

- *P2L6: Last sentence needs rewriting.*

ANS: Revised as suggested

- *P2L15: Sentence needs rewriting: “This approach, however,...”*

ANS: Revised as suggested

- *P2L31-32: Delete last sentence of this paragraph. It is mis-leading as all of the mentioned aerosol-coupled regional models include a coupling of the cloud microphysics to the radiation.*

ANS: Revised as suggested

- *P3L22: Sentence needs rewriting: “In this study, the COSMO model...” Equation 5: Change $\frac{1.5}{2}$ to $\frac{3}{4}$.*

ANS: In this study, COSMO model has been configured in a non convection permitting mode with uniform horizontal grid resolution of 0.25° (≈ 28 km).

$$\tau_c = \frac{3\rho_{qc}dz}{2\rho_w\Gamma_e} \quad (2)$$

- *P4L23: Sentence needs rewriting: “IN the COSMO model, the aerosol...”*

ANS: Revised as suggested

- *P5L1-11: This discussion needs some clarification: How is the $S_{\max}$ issue raised overcome? You raise the issue of ignoring updraft velocity in the Boucher and Lohmann formulation, however, is this then not introduced by $dS/dz \cdot w$ in Eq.7 (which admittedly is a very simplistic formulation of this relationship).*

ANS: In this case simulations are carried out for intermediate aerosol condition, in which $S_{\max}$ is set at 2.0%. Boucher and Lohmann parameterization is bound to updraft velocity uncertainty, however it can be overcome by $dS/dz \cdot w$ in Eq.7. This part is revised.

- *P5L20ff: Here you list all satellite products used for evaluation. Also include CERES here, as you use it later.*

ANS: Revised as suggested

- *P5L27: I suggest to delete: In the upcoming... You have 1 ISCCP figure, 2 Modis and 1 CERES. That is not massively unbalanced.*

ANS: Revised as suggested

- *P5L30: I suggest to delete last sentence of this paragraph.*

ANS: Revised as suggested

- *P5L25-30: Please rephrase. The point regarding satellite biases could be formulated like: "One should keep in mind that the satellite products, just like models, are prone to biases. Comparisons of satellite retrievals with ... have shown that.... Nonetheless, spatial correlation of the cloud structures are well represented."*

ANS: Revised as suggested

- *P6L2: Sentence needs rewriting: "As the forecast time..."*

ANS: Revised as suggested

- *P6L10: Results are only shown for 17th. Not 15th – 25th. Please include description of the cloud types of this domain (altitude, phase, average thickness, surface precipitation). When did you start your simulation, cause the 2nd day would be the 16th if the simulation were started in the morning of the 15th? Also, why are is the 16th not included in the analysis?*

ANS: In the revised manuscript, synoptic conditions for 15 Feb (Figure S1) and 17 Feb (Figure 2) are included along with cloud type. Simulation started at 15 Feb, 00.00 hrs, then 17-Feb would be the third day of the simulation (Revised in the manuscript).

- *P6L22-25: First 3 sentences should go into section 2.1.1 (methods).*

ANS: Revised as suggested

- *P7L1-4: First 3 sentences should go into section 2.1.1 (methods).*

ANS: Revised as suggested

- *P7L6: "The top panel shows...." This should be in Fig. Caption.*

ANS: Revised as suggested

- *P7L19: Please check units.*

ANS: The unit has been corrected to kgm^{-2}

- *P7L25-30: In this discussion quantitative statements should be included. For instance, the area mean changes + variability could be determined. It would help determine the signal from the noise in figures g to i.*

ANS: For quantitative comparison, PDF distribution of cloud products are included in the

analysis.

- *P8L14: First sentence of paragraph need rewriting/clarification.*

ANS: Sentence rephrased: While comparing modified two-moment scheme results with MODIS level-2 satellite products, the model shows more cloud free (clear) grid points. This indicates that model is unable to capture the sub grid scale cloud patterns accurately (Jason and Thomas, 2008), which may be due to the coarse resolution (0.25°) of the model.

- *P8L19: Maybe rephrase title, because aerosol-cloud radiation interactions were already discussed in previous section (cloud optical thickness). Suggestion: "Impacts on radiative balance" In general this discussion is not very precise. It would help the discussion if you relate observed changes in e.g. the SW fluxes to the decrease in cloud optical thickness...*

ANS: Revised as suggested

- *P8L30: Please rephrase. It is an initial approach to modify COSMO-MUSCAT only.*

ANS: Revised as suggested

- *P9L7: Finding 1 should be removed as it is not discussed in the paper.*

ANS: Finding 1 has been changed to: "The modified two-moment scheme results have been compared with two-moment version of COSMO model. In terms of the cloud distributions, this modification has only a minor effect".

- *P9L13: Paragraph missing after point 2.*

ANS: Revised as suggested

- *P9L22: Last sentence needs rewriting and one reference is missing.*

ANS: Sentence rephrased: This can result in more precise cloud droplet activation parameterization, involving different aerosol species as CCN, and thus improving the cloud droplet number calculation of Lohmann et al., (2007).

- *P10ff: A few references need changing. Some paper titles use capital letters. IPCC reference is incomplete*

ANS: Revised as suggested

- *Fig1: More detail should be given in the caption. I think this figure could be improved/clarified. Why are the "emissions/land use" and M7 stand-alone and not connected? The figure could be clearer regarding the structure of the code. Are RACM and MUSCAT separate modules? Will M7 not be embedded in MUSCAT? Is the output really completely separate?*

ANS: Figure 1 has been modified, COSMO-MUSCAT is an online coupled modeling system, which uses COSMO meteorological fields to drive the model. Emissions and land use data are in input for MUSCAT model and RACM is a module, which is included in MUSCAT. In this particular version of COSMO-MUSCAT(V5.0), M7 not yet embedded. Also, the outputs are separate.

- *Fig2: I personally would not include all "H" and "L" markes. I would simply mark the center of the dominant low pressure and high pressure systems.*

ANS: Revised as suggested

- *Fig3/Fig4: Looking at these figures optically, I would arrive at different cloud fractions for Fig3b and Fig4d. Areas where the total cloud fraction of the model is 100%, the diagnosed*

optical thickness is 0 or just very small? Does the COSP simulator include subgrid-scale cloud water? If not, is that justified for cloud optical thickness?

ANS: ISCCP satellite observations are available with 280 km resolution, for the comparison COSP derived ISCCP output (28 km) are re-gridded to 280 km, which is stated in the manuscript. The cloud water simulated at sub-column within model grids account for subgrid-scale variability.

- *Fig4: Maybe regional/domain means + a measure of variability could be given to highlight the results more quantitatively?*

ANS: For quantitative comparison, PDFs are used, instead of regional means, which may add uncertainty.

- *Fig5: What is going on with the MODIS cloud droplet number estimate? Why is the spatial pattern so different than in Fig4a-c. Are these clouds just too shallow to obtain a good number estimate?*

ANS: CDNC can be derived from MODIS cloud optical depth τ_c and effective radius r_e (Quaas et al., 2009), which is given by,

$$N_d = \alpha \tau_c^{0.5} r_e^{-2.5} \quad (3)$$

where $\alpha = 1.37 \times 10^{-5} \text{m}^{-0.5}$. In the above equation the lower limit of τ_c and r_e are constrained to 5 and 2. This would result in low CDNC in figure 6c.

- *Fig6/Fig7: I find the color scale depicting the fluxes very misleading. I would suggest using a pure blue color scale for LW fluxes and pure red for SW fluxes.*

ANS: Revised as suggested

Reviewer Comments:3

The authors present a numerical study on aerosol, clouds and radiation with mutual interactions and compare the results with satellite derived data. . This is an important topic, since all cloud-related processes pose a severe problem in weather forecast and climate modeling. The paper contributes to the ongoing research by examining the effect of mutual interactions of these processes and the improvement of atmospheric models. This is worth to be published. The presentation is concise, length and number of figures are appropriate. However, the presentation is partly very vague and not consistent throughout the paper. The differences between the resp. data fields are inspected by eye, but not quantified. Therefore, it is difficult to follow the conclusions. Errors in some equations may be typos. Yet, before publication, I suggest some substantial revisions. Please see the major points and specific remarks below.

Major Points:

- *In mid-latitude winter I expect that the ice phase plays an important role in the development of clouds and precipitation (Bergeron-Findeisen effect!), and you use the Seifert and Beheng (2006) scheme for mixed phase clouds. The paper, however, is devoted to the liquid phase alone. Please discuss the effect of the modified treatment of drop nucleation on the ice phase properties, since a modification in one path of condensate formation is connected with an opposing trend in other path(s).*

How do you determine the effective radius under cloud free conditions?

ANS: Even though SB scheme is for mixed phase clouds, heterogeneous ice nucleation is not included in the official version of COSMO. Also, Seifert et al., (2012) has demonstrated the importance of heterogeneous ice nucleation by adding Philip et al., (2008) parameterization (not available with official version). Hence, to reduce the uncertainty in aerosol cloud interaction, we have restricted our analysis to liquid phase clouds only. Moreover, our main objectives are to modify the fixed CCN in two-moment scheme with online coupled COSMO-MUSCAT model and incorporate COSP satellite simulator in it. In future we will be addressing aerosols as INP. Additionally, cloud ice optical properties on 17 February shows that (Figure 1), the study area is dominated by liquid phase clouds rather than ice clouds.

In satellite observation, cloud droplet number concentration can be derived from MODIS cloud optical depth τ_c and effective radius r_e (Quaas et al., 2009), which is given by,

$$N_d = \alpha \tau_c^{0.5} r_e^{-2.5} \quad (4)$$

where $\alpha = 1.37 \times 10^{-5} \text{m}^{-0.5}$. In the above equation the lower limit of τ_c and r_e are constrained to 5 and 2. This would result in low CDNC value across the domain (Figure 6c).

- *Equations (3) - (5) (3) holds if the cloud drop size distribution is used with the internal coordinate drop diameter D , not radius r . Then, (4) follows as*

$$\lambda = \left[\frac{\pi \rho_w N \Gamma(\mu + 4)}{6 \rho_{qc} \Gamma(\mu + 1)} \right]^{\frac{1}{3}} \quad (5)$$

with ρ is air density, ρ_w is bulk density of liquid water, q_c is mass fraction of liquid water, N number of drops per volume.

(5) requires some explanations as for the inherent assumptions to be reproduced by the reader. A familiar model for the optical thickness (see e.g., Salby: Atmospheric Physics. Academic Press, 1996, Eq.(9.45)) gives

$$\delta = \frac{3 \rho_{qc} dz}{2 \rho_w r_e} \quad (6)$$

which differs by a factor of 2 from (5). Please clarify.

ANS: The cloud droplet size distribution is represented by gamma function, which is used with drop diameter.

$$\phi(D) = N_o D^\mu e^{-\lambda D} \quad (7)$$

where D is droplet diameter, λ is slope parameter and μ is spectral shape parameter. Whereas the effective radii for droplets and cloud ice are obtained directly by dividing the third and second moments of the size distribution given by (Morrison et al., 2008)

$$r_e = \frac{\Gamma(\mu + 4)}{2\lambda\Gamma(\mu + 3)} \quad (8)$$

Equation 5 is corrected to

$$\delta = \frac{3\rho q_c dz}{2\rho_w r_e} \quad (9)$$

- *The nucleation rate (7) is connected with supersaturation S . Small but inevitable errors in vapor concentration q_v signify huge relative deviations in S . Can you estimate the resulting uncertainty in the nucleation rate?*

Do you have a full prognostic equation for supersaturation S or do you use saturation adjustment to calculate S ? In the second case, some more information is required for the calculation of the nucleation rate by (7). How do you get a supersaturation $S > 0$ despite adjustment?

The uncertainty of calculation of S occurs in all schemes using an equation such as (7).

I wonder whether it is helpful to introduce more physical details on the nucleation rate as long as the basic property S carries such an uncertainty. Please comment. The size of a freshly nucleated droplet is to be prescribed. What do you assume?

ANS: In COSMO model, nucleation rate is parameterized as a function of grid scale supersaturation and vertical velocity. It uses saturation adjustment to calculate S . Also, It is logical to use nucleation scheme explicitly depending on supersaturation in combination with saturation adjustment, which is done by applying an operator splitting method (Seifert et al., 2006). For SB parameterization the arbitrarily chosen small droplet mass is given by 1×10^{-12} kg, and corresponding size of freshly nucleated drop is $6.2 \mu\text{m}$. A detailed explanation is available in Seifert et al., 2006.

- *Problem of averaging.*

p. 7, Figs. 4,5. Cloud water path is a property defined for the whole air column. Cloud effective radius, cloud droplet number concentration, and sulfate aerosol number concentration are defined locally, and for a grid point model the data are interpreted to be representative for the grid cell. For which level are the given data relevant? If they are vertical averages, please discuss, how the vertical average is calculated, how cloud free layers are considered, how the result is to be interpreted, etc. This point is even more complicated for the local variable r_e , which depends nonlinearly on the local variables N and q_c . Likewise, optical thickness is defined for a certain layer of thickness dz , maybe the layer where the respective r_e holds. The presented fields depend on the averaging method.

The same question arises for the daily averaging procedure and concerns also liquid water path. It concerns both, model and satellite data. Please explain, and correct the discussion where necessary. See Specific Points.

ANS: COSMO and COSMO-MUSCAT models are incorporated with COSP satellite simulator (Bodas-Salcedo et al., 2011). The variable such as, cloud water path, cloud optical depth, effective radius and sulfate aerosol number concentration are derived from COSP satellite simulator, which are vertically averaged.

To produce similar output to satellite data, COSP requires grid mean vertical profile of temperature, humidity, hydrometer mixing ratio, cloud optical thickness and emissivity,

surface temperature and emissivity from the model. It produces the output comparable with satellite data in three steps. First it address the mismatch between model and satellite pixel, second vertical profiles of individual sub-columns are passed to each instruments and finally COSP statistic module gather the output from all instruments (Bodas-Salcedo et al., 2011). The above paragraph is included in the revised manuscript (Section 2.2).

- *Drop number concentration, liquid water content and path, optical thickness, and effective radius are interrelated, not independent of each other. Fig. 4 shows a strong correlation between optical thickness and cloud water path, as expected. The effective radius distribution shows a different pattern, somewhat inversely to the drop number concentration in Fig. 5; for same liquid water content, a lower N_d means a larger r_e , see e.g. the relationships (3) - (5). This relation should be taken into account in the interpretation of Figs. 4 and 5. For the discussion of the improvement of COSMO-MUSCAT to COSMO-2M it would be helpful to include the COSMO-2M-fields in Fig. 4 besides (or instead of) the difference fields.*

ANS: There was an error in Figure 4, which is corrected in the manuscript. In the corrected version, there is correlation between cloud optical depth, effective radius and liquid water path. The difference between COSMO-MUSCAT and COSMO-2M would more relevant than COSMO-2M.

- *The choice of the parameters C_{ccn} (p. 4 bottom) is a good general guess, however, not a universal constant. Did you do a similar run with modified C_{ccn} -values to check the influence - in opposition to the influence of the full interactive treatment with MUSCAT? COSMO-MUSCAT seems to result in much smoother distributions than COSMO-2M, in particular Fig. 5. Do you have an explanation?*

ANS: In the interactive model (COSMO-MUSCAT) the general guess has been replaced by C_{ccn} calculated using equation 8.

In the revised manuscript, Figure 6(a to c) has been modified. In order to compare the model simulation with satellite observations, we have used equation (9) to compute model N_d , as the COSP simulator can provide cloud optical depth and effective radius similar to MODIS satellite.

In COMSO-2M, we have used intermediate aerosol ($C_{ccn} = 3.0 \times 10^8 \text{ m}^{-3}$), when it comes to COSMO-MUSCAT interactive simulation, it uses gridded C_{ccn} information from MUSCAT.

From Figure 6d it is noticed that the maximum value of sulfate aerosol number concentration is in the order of $3.0 \times 10^8 \text{ m}^{-3}$, however the droplet activation is controlled by several other meteorological properties such as vertical velocity and micro-physical links.

- *The aerosol-cloud-radiation interaction is an important point, since it affects directly the energy budget. Unfortunately, the discussion is limited to a description of Figures 6, 7, and no information on the cloud related parameters of COSMO-2MR are given. Either this aspect should be strengthened or skipped.*

ANS: This part has been revised.

- *The wording and the comparison can be more straightforward and more precise throughout the paper. Please work over the whole text. This concerns in particular the data intercomparison, which is done on a subjective basis phrasing like 'the differences are small'. Please quantify your statements for objective conclusions. Otherwise, e.g., the conclusion of superiority of COSMO-MUSCAT is not a priori clear from the case study, in particular since the difference between the MODIS data and each model result is larger than the difference between two model versions.*

Please also interpret systematic differences in terms of the model modifications. Might it be

possible that parts of the differences between data from simulation and satellite are due to a) different cloud distributions and b) different instants of time used for the daily average?

ANS: The wording and the comparisons are revised in the manuscript.

Specific points

- *Introduction: The section can be written in a more compact way. In particular, the 1 and 2-moment schemes should be discussed primarily with regard to the aerosol-cloud and cloud radiation feedbacks.*

l.33: What is the outcome of Seifert et al. (2012)?

ANS: Introduction is revised. l.33: Seifert et al. (2012) reported that in COSMO model, radiative aerosol induced effects are more relevant than effect on precipitation. They have shown that, one-moment scheme has a strong positive bias in maximum 2m temperature. This difference between one-moment and two-moment scheme may partly explained by different cloud-radiation coupling.

- *p. 5, subsubsection 2.1.1. should read 2.2. This short para has the character of an introductory explanation, but none of the methods is explained. Please give some more informations, e.g. in form of a short table as overview of all satellite data sources (ISCCP, CALYPSO, CERES, MODIS ...?), including informations of spatial and temporal resolution for the averaging aspect. Do you use all mentioned satellite data?*

l. 19: I do not understand 'the assumptions for the satellite retrievals' in this context. COSP is important for the paper. Please explain what the simulator does, at least the input and output data, and what kind of errors may occur.

What kind of spatial and temporal averaging is done? E.g., how many output times do you have for COSP- and for satellite data to determine a daily mean value? Can the averaging procedures produce a bias in the results, maybe the difference in daily averaged cloudiness in Figure 3?

What is the physical interpretation of a 'daily mean cloud cover'? 12h cloud free plus 12 h full cloud cover results in 50% cloudiness?

ANS: subsubsection 2.1.1. is revised to 2.2.

More information regarding the satellites are included in the manuscript. p5, l.9 has been rephrased: However, a meaningful evaluation of modeling with satellite observations is challenging because of the difference in the model variables and the satellite retrievals.

To produce similar output to satellite data, COSP requires grid mean vertical profile of temperature, humidity, hydrometer mixing ratio, cloud optical thickness and emissivity, surface temperature and emissivity from the model. It produces the output comparable with satellite data in three steps. First it addresses the mismatch between model and satellite pixel, second vertical profiles of individual sub-columns are passed to each instruments and finally COSP statistic module gathers the output from all instruments (Bodas-Salcedo et al., 2011). Since COSP is running online with COSMO model, it is able produce output similar to model simulation (in every hour).

An important aspect of COSP satellite simulator is positional errors due to mismatch between meteorological regimes in the observation and models, which is not considered.

- *p.5 Section 3.1: The synoptic situation should be described for the situation on 17 February, the day of the later discussion and evaluation.*

ANS: Revised as suggested.

- *p.6 l. 16. 'Northerly wind'? Fig. 2 shows mostly south-westerly winds over the Atlantic.*

ANS: Revised.

- p.6 l. 18-19. Please precise the sentence 'The cold continental air mass ...'.

ANS: Revised.

- In Section 3, you use 3 version of the COSMO model and several satellite data sets for mutual intercomparison. Please make clear everywhere, which respective data sets are compared, and break the passages of different intercomparisons. Please use always the same expressions. E.g. p.7 l. 2. Which two model versions? What is the 'MODIS simulator' (also l. 30)?

ANS: P7, l.2: this line is removed from the manuscript. P7, l.30: We have also included cloud droplet number concentration N_d as a diagnostics of the model via COSP satellite simulator (MODIS simulator in COSP).

- Section 3.2 (in particular) contains inconsistencies in wording and notation compared to the rest. E.g., optical depth δ vs. τ_c , COSP satellite simulator vs. MODIS satellite simulation? Please unify.

ANS: Revised

- p.7 l.11pp. The spatial structure of the fields are similar. On the linear scale, I would not agree to 'slightly larger' (l. 11) or 'slight underestimation' (l. 18). I am well aware that both data sets are subject to many sources of error, hence a similar field structure and a similar order of magnitude should be acceptable, but not whitewashed.

P.7, l. 14pp. The strongest differences do not occur near the Atlantic coast, but in the most western part of the domain. I have the impression that the model does not catch these clouds. Please clarify.

ANS: P7, l.11, rephrased to: In satellite, it varies between 5 to 54 and in model between 5 to 45, with maximum values observed over similar geographical regions. However, the satellite derived cloud optical depth and liquid water path are overestimated while comparing with model (COSMO-MUSCAT) outputs.

P7, l.14: this sentence has been removed.

- p. 7 l. 19. Correct unit of cloud water path.

ANS: Revised as suggested.

- p.7 l.20pp Fig.4 g-i. I do not follow your interpretation. The differences should be seen in relation to the signal. The least (relative) difference should be seen in the LWP, since the amount of condensate is primarily determined by other than microphysical processes and is to be seen in relation to the change in cloud ice. The sequel of e.g., red and blue bands over the Biscaya may be a phase shift. A decrease of re by $10\mu m$ is of the order of the signal, not a 'slight reduction'.

Please precise. I agree with your conclusion of l. 27-28. However, I cannot see the superiority of COSMO-MUSCAT from the present material.

ANS: Revised

- p.7 l. 25. Again: Not 'slight' and 'little'.

ANS: Revised

- p.8 l.3. 'cloud microphysics are modified'. If this is worth mentioning, then please be more precise

ANS: Revised

- p.8 l.3. Please explain what you mean by 'better agreement'. Allgemeine FRAGE!!

ANS: This part is revised: Even though, the satellite derived N_d has poor spatial distribution, the N_d values are underestimated while comparing with COSMO2M and it is overestimated while comparing with COSMO-MUSCAT

- p.8 l.6. Fixed $CCN = 300 \text{ cm}^{-3}$ in COSMO-2M? This is in contradiction to Section 2.1, telling N_{ccn} is given as function of S .

l. 32. Similar: 'constant cloud condensation nuclei profile'?? Please clarify.

ANS: In COSMO-2M N_{ccn} is a function of S , whereas C_{ccn} kept constant. In the coupled model constant C_{ccn} in the two-moment scheme is replaced by gridded C_{ccn} proxy from MUSCAT, which is four dimensional.

- p.8 l. 9pp. The aerosol NUMBER (not 'mass') concentration is given in Fig. 5c. Could you please comment on the fact, that Sulfate is so much larger than N_d for COSMOMUSCAT? Is the result of Boucher and Lohmann (1995) transferrable to your model concept?

ANS: The main objective of this paper is the replace the constant C_{ccn} , in COSMO2M(COSMO two-moment), with interactive aerosol from MUSCAT model. Since the MUSCAT model is available with aerosol mass concentration (in this case sulfate aerosols), we have used Boucher and Lohmann parameterization to calculate C_{ccn} number concentration from mass concentration.

- p.8 l.14pp Please revise the para.

'the model exhibits more clear grid points.' What do you mean?

'The model is unable to capture sub grid scale cloud patterns': A subgrid scale cloud cannot be captured by the microphysics parameterization of Seifert and Beheng (2012) or similar ones. You would need a different tool.

'the satellite may overestimate the retrievals.' What do you mean?

ANS: This paragraph has been revised. clear grid means, cloud free region, which is also revised in the manuscript.

- p. 8, Section 3.3. l. 25. '(20 to 20 Wm^{-2} ' ?? 'some regions': Please precise Fig. 6. The colorbars are differently scaled for most of the subfigures. Sometimes this is straightforward (e.g., a and f vs. b and f), sometimes, however, confusing (e.g. a vs.c, j vs. l). Please unify the scaling.

Please also consider to plot the net UPWARD LWF to have the colors consistent to the SWFs, e.g., blue for weak differences. Same for Fig. 7.

Fig. 7 a-d contains is repetition of Fig. 6 e-h. Use the difference fields COSMO2M rad minus CERES instead.

- l. 27/28. I cannot follow the statement 'the differences are neither systematic nor large'. Please interpret the radiative flux differences also in terms of the cloud properties.

ANS: Revised to Northern part of the domain. Color scale of Figure 6 & 7 are revised. Line 27/28 has been removed from the manuscript.

- p. 9 l. 7pp

Please check the conclusions with regard to the above points for more precise statements. Conclusion 1. If you refer to the model runs COSMO-2M and COSMO-MUSCAT, please say so. Then, this statement does not agree with p.7 l. 20-29. Please clarify.

Conclusion 2. Precise the 'modified model simulation'.

ANS: Revised as suggested.

- p9 l21. Missing reference.

ANS: Revised as suggested.

- *If a paper is written by two authors, please cite as 'A and B (1999)'*

ANS: Revised as suggested.

- *p.11: Citation of IPCC is incomplete.*

ANS: Revised as suggested.

- *Please check ALL figures w.r.t. wording within the plots and in the legends. E.g., in Fig. 2 'Temperature', in Fig.3 'MUCAT', in Fig. 4 g-i 'CSOMO2M'.*

ANS: Revised as suggested.

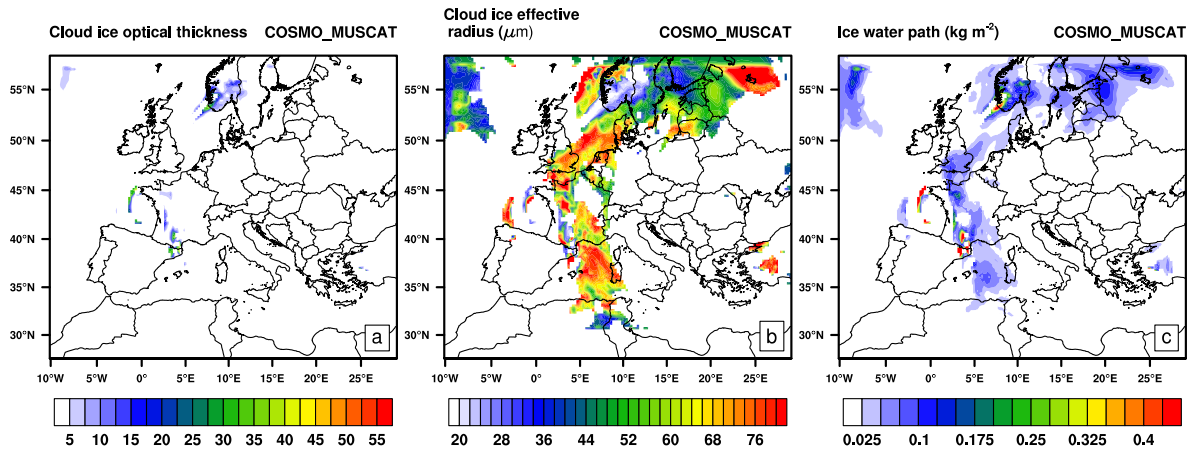


Figure 4: COSMO-MUSCAT cloud ice optical properties on 17 February 2007.

Implementation of aerosol-cloud interactions in the regional atmosphere-aerosol model COSMO-MUSCAT(5.0) and evaluation using satellite data

Sudhakar Dipu¹, Johannes Quaas¹, Ralf Wolke², Jens Stoll², Andreas Mühlbauer³, Odran Sourdeval¹, Marc Salzmann¹, Bernd Heinold², and Ina Tegen²

¹Institute for Meteorology, Universität Leipzig, Germany

²Leibniz Institute for Tropical Research, Germany

³FM Global Research, Norwood, MA, U.S.A

Correspondence to: Dipu Sudhakar (dipu.sudhakar@uni-leipzig.de)

Abstract. The regional atmospheric model Consortium for Small Scale Modeling (COSMO) coupled to the MultiScale Chemistry Aerosol Transport model (MUSCAT), is extended in this work to represent aerosol-cloud interactions. Previously, only one-way interactions (scavenging of aerosol and in-cloud chemistry) and aerosol-radiation interactions were included in this model. The new version allows for a microphysical aerosol effect on clouds. For this, we use the optional two-moment cloud microphysical scheme in COSMO and the online-computed aerosol information for cloud condensation nuclei (CCN) concentrations, replacing the constant CCN concentration profile. In the radiation scheme, we implement a droplet-size-dependent cloud optical depth, allowing now for aerosol-cloud-radiation interactions. In order to evaluate the model with satellite data, the Cloud Feedback Model Inter-comparison Project Observational Simulator Package (COSP) has been implemented. A case study has been carried out to understand the effects of the modifications, in which the modified modeling system was applied over the European domain with a horizontal resolution of $0.25^\circ \times 0.25^\circ$. **Further, to reduce the complexity in aerosol cloud interaction only warm-phase clouds are considered.** It is found that the online coupled aerosol introduces significant changes for some cloud microphysical properties. The cloud effective radius shows an increase of **1 to 4 μm** , and the cloud droplet number concentration is reduced by 100 to 200 cm^{-3} . For both quantities, the new model version shows a better agreement with the satellite data. The microphysics modifications have a smaller effect on other parameters such as optical depth, cloud water content, and cloud fraction.

1 Introduction

The quantification of aerosol cloud interactions in models continues to be a challenge (IPCC, 2013). Estimates of effective radiative forcing and assessments of the radiative effects due to aerosol cloud interactions to a large extent rely on numerical modeling. A large effort has been made to represent such effects in general circulation models (GCM) (Penner *et al.*, 2006; Quaas *et al.*, 2009; Ghan *et al.*, 2016). However, GCMs do not resolve the processes relevant for cloud dynamics well. Improved process understanding for aerosol-cloud interactions thus largely relies on simulations with cloud-resolving and

large-eddy simulations (LES) (Ackerman *et al.*, 2000, 2004; Xue *et al.*, 2006; Sandu *et al.*, 2008; Seifert *et al.*, 2015; Berner *et al.*, 2013). However, LES often focus on case studies and use idealised boundary conditions and also an idealised representation of the aerosol. This leads to uncertainties in particular because, when analyzing cloud systems, or cloud regimes, rather than individual clouds, aerosol-cloud-precipitation interaction processes often are buffered (Stevens and Feingold, 2009). Regional climate modeling is a powerful tool to overcome these limitations of small-domain, idealised LES. Much higher resolutions are possible than for GCMs. Compared to LES that only simulate individual cloud systems, feedbacks between clouds and aspects of the large-scale circulation and its variability are simulated by regional climate models. ***Even though regional models do not describe part of the large scale feedbacks, it provides optimal compromise*** (Bangert *et al.*, 2011; Van den Heever and Cotton, 2007; Chapman *et al.*, 2009; Forkel *et al.*, 2015; Yang *et al.*, 2012).

A still often applied cloud microphysics parameterization in numerical weather prediction is a bulk, one-moment scheme (Kessler, 1969; Lin *et al.*, 1983), which uses the specific mass for different hydrometeor species as prognostic variables. However, it cannot treat aerosol cloud interaction because only one moment of the size distribution is calculated, do not carry information about size or number concentration of cloud droplets. In contrast, bin microphysical schemes numerically resolve the size spectrum and are thus able to predict the spatio-temporal behavior of a number of size categories for each hydrometeor explicitly (Khain *et al.*, 2000; Simmel *et al.*, 2015). ***However, this approach is numerically very expensive especially when applied for regional atmospheric models.*** As a compromise between these two approaches, two-moment microphysical schemes are able to predict the number concentration of the liquid and ice hydrometeors, in addition to mass variables (Cotton *et al.*, 1986; Meyers *et al.*, 1997; Seifert and Beheng, 2006). Furthermore, numerous studies have shown that two-moment scheme is a promising avenue to be used in future operational forecast models (Reisner *et al.*, 1998; Tao *et al.*, 2003; Seifert and Beheng, 2006) and is also computationally efficient.

At present, several weather prediction and global models have applied two-moment cloud microphysical schemes. For example, the Weather Research and Forecasting model (WRF) is available with different types of two-moment microphysical schemes (Thompson *et al.*, 2008; Morrison *et al.*, 2008; Lim *et al.*, 2010). Morrison *et al.* (2009) demonstrated the trailing stratiform precipitation in an idealized two-dimensional squall case with WRF model, which is consistent with surface observations. In another study, Li *et al.* (2008) investigated the effect of aerosol on cloud microphysical processes with a two-moment microphysical scheme in WRF model. Also, Lim *et al.* (2010) have included the prognostic equation for cloud water and cloud condensation nuclei (CCN) number concentration, which could reduce the uncertainty to investigate the aerosol effect on cloud properties and the precipitation process in WRF model. Furthermore Weverberg *et al.* (2014) discuss the comparison between one-moment and two-moment microphysical schemes in the Consortium for Small Scale Modeling atmospheric model (COSMO). ***Further, other groups previously implemented aerosol-cloud interactions in COSMO, albeit with a different aerosol scheme*** (Bangert *et al.*, 2011; Zubler *et al.*, 2011; Possner *et al.*, 2015) ***and very few are coupled to the radiation scheme*** (Seifert *et al.*, 2012). ***Seifert et al. (2012) reported a strong positive bias while comparing 2-m temperature in operational one-moment scheme with cloud radiation coupled two-moment scheme, which indicates that radiative aerosol induced effects are more relevant than effect on precipitation***

In this paper we discuss the improved cloud microphysics parameterization in the COSMO model (*Doms et al.*, 1999), via the online-coupled aerosol model, MUlti-Scale Chemistry-Aerosol Transport (MUSCAT; (*Wolke et al.*, 2004, 2012)). The two-moment cloud microphysical scheme in the COSMO model (*Seifert and Beheng*, 2006) uses fixed profiles of CCN concentrations. Rather than this simplification, here we use CCN concentrations predicted on the basis of the simulated aerosol from the MUSCAT module. This will enable the COSMO model to have temporally and spatially varying CCN concentrations at each grid point, which are fully consistent with the cloud and precipitation fields, as well as with dynamics (e.g. scavenging is taken into account, as is vertical transport) to represent aerosol cloud interactions. In two further steps, (i) the radiation scheme is slightly revised to take into account the cloud droplet size information (so far considered constant even when applying the two-moment cloud microphysical scheme), and (ii) a diagnostic tool, the Cloud Feedback Model Intercomparison Project Observational Simulator Package (*Bodas-Salcedo et al.*, 2011, 2008; *Nam and Quaas*, 2012) is implemented that allows for a consistent evaluation using satellite observations. The paper is organized as follows; section 2 gives a brief introduction to the coupled model systems, data and methodology. The comparison between the improved two-moment cloud microphysical parameterization with the available two-moment scheme making use of the COSP satellite simulator is discussed in section 3. Finally, concluding remarks are given in section 4.

2 Data and Methodology

2.1 The COSMO-MUSCAT model and revised cloud activation

The non-hydrostatic three-dimensional model, COSMO developed for limited-area operational predictions (*Doms et al.*, 1999; *Steppeler et al.*, 2003) is used in this study. This model has been used operationally in convection permitting configurations since 2007 by the German Weather Service (Deutscher Wetterdienst, DWD) (*Baldauf et al.*, 2011). In this study, we have used COSMO version 5.0, which is initialized and forced by reanalyzed data provided by the global meteorological model GME (Global Model of the Earth) of DWD, which is a hydrostatic weather prediction model (*Majewski et al.*, 2002). GME operates on an icosahedral hexagonal grid having a horizontal resolution of approximately 40 km and vertical resolution of 40 layers up to 10 hPa. The COSMO model is initialized with the interpolated GME initial state and nested within GME with hourly updates of lateral boundary values. *In this study, COSMO model has been configured in a non convection permitting mode with uniform horizontal grid resolution of 0.25° (≈ 28 km).* The two-moment scheme in COSMO model consists of five hydrometeors classes, namely cloud droplets, rain, ice crystals, snow and graupel. Processes considered by this scheme include the nucleation of cloud droplets, autoconversion of cloud droplets to form rain, accretion and self-collection of water droplets. The formulations have been derived by *Seifert and Beheng* (2001) from the theoretical formulation of *Beheng and Doms* (1986). However, the radiation scheme does not yet make use of the additional information about cloud particle sizes provided by the two-moment microphysics. It uses the *Ritter and Geleyn* (1992) parameterization for the cloud optical properties in radiation scheme. According to *Ritter and Geleyn* (1992), the cloud optical properties were approximated by the relation between specific liquid water content q_c and cloud effective radius r_e of cloud drop size distribution, thus cloud optical

depth τ_c is expressed as,

$$\tau_c = (c_1 + \frac{c_2}{r_e})q_c dz \quad (1)$$

where dz is layer thickness, and c_1 and c_2 are constants. Similarly, the effective radius r_e is related to specific cloud water content and is approximated as,

$$r_e = c_3 + c_4 q_c \quad (2)$$

where c_3 and c_4 are constants (*Ritter and Geleyn, 1992*). In order to take into account of the two-moment microphysics scheme, the simulated variable cloud droplet size, the cloud optical properties in radiation scheme have been modified. The cloud effective radius r_e is derived by dividing the third and second moment of the size distribution (*Martin et al., 1994*) which, after rearranging, yields,

$$r_e = \frac{\Gamma(\mu + 4)}{2\lambda\Gamma(\mu + 3)} \quad (3)$$

where μ is spectral shape parameter, Γ is gamma distribution function and λ is the slope parameter, which is given by

$$\lambda = \left[\frac{\pi\rho N\Gamma(\mu + 4)}{6q_c\Gamma(\mu + 1)} \right]^{\frac{1}{3}} \quad (4)$$

where ρ is the density of the air, N is the droplet number concentration, and q_c is the specific water content. The corresponding cloud optical depth is given by

$$\tau_c = \frac{3\rho q_c dz}{2\rho_w r_e} \quad (5)$$

where, dz is the layer thickness, $\rho_w = 1000 \text{ kg m}^{-3}$ the density of liquid water.

The online coupled model system COSMO-MUSCAT (*Wolke et al., 2012; Renner and Wolke, 2010; Wolke et al., 2004*) is used for prognostic cloud condensation nuclei in the cloud microphysics parameterization in COSMO model. The chemistry/aerosol transport model, MUSCAT treats atmospheric transport as well as chemical transformation, with the Regional Atmospheric Chemistry Mechanism (RACM) (*Stockwell et al., 1997*). In MUSCAT, all meteorological fields are given with respect to the uniform horizontal meteorological grid from the online coupled COSMO2M (COSMO with two-moment scheme) model, whereas the aerosol information is fed back to the COSMO2M model from MUSCAT. In the previous setting, the interactions only considered the radiative effects of aerosols (scattering and absorption of solar radiation), as well as the scavenging of aerosol and in-cloud aerosol chemistry. A diagram illustrating the COSMO-MUSCAT modeling set up is shown in Figure 1. ***In COSMO model, the aerosol activation parameterization is based on empirical activation spectra, which is in the form of power law relation,***

$$N_{ccn} = C_{ccn} S^k, \text{ } S \text{ in } \% \quad (6)$$

where S is supersaturation, $C_{ccn} = 1.26 \times 10^9 \text{ m}^{-3}$, and $k = 0.308$ for continental condition or $C_{ccn} = 1.0 \times 10^8 \text{ m}^{-3}$ and $k = 0.462$ for maritime condition (*Khain et al., 2001*). Accordingly, the grid scale explicit nucleation rate is calculated from the

time derivative of activation relation (Seifert and Beheng, 2006),

$$\left. \frac{\partial N_c}{\partial t} \right|_{nuc} = \begin{cases} C_{ccn} k S^{k-1} \frac{\partial S}{\partial z} w, & \text{if } S \geq 0, w \frac{\partial S}{\partial z} > 0, \\ & \text{and } S < S_{max}, \\ 0 & \text{else.} \end{cases} \quad (7)$$

The above parameterization scheme uses constant C_{ccn} concentrations in accordance with different atmospheric conditions. Also, S_{max} varies with atmospheric conditions (maritime C_{ccn} assumes that at $S_{max} = 1.1\%$, all C_{ccn} are already activated).

- 5 ***In the above equation, nucleation is explicitly depends on grid scale supersaturation in combination with saturation adjustment, which has limitation. This has been over come by applying an operator splitting method to treat process numerically (Seifert and Beheng, 2006). As an initial step, coupled model simulation is carried out by setting $S_{max} = 2.0\%$, which is the optimum condition for intermediate aerosols in COSMO model. Further, we have used simulated sulfate (SO_4) aerosol mass concentration information from MUSCAT model (The emission inventory in MUSCAT model is proved by TNO for the***
- 10 ***Air Quality Model Evaluation International Initiative (AQMEII) project (Pouliot et al., 2012)) to derive C_{ccn} concentration proxy using the following empirical relation (Boucher and Lohmann, 1995),***

$$C_{ccn} = 10^{2.21+0.41\log(mSO_4)} \quad (8)$$

where mSO_4 is the sulfate aerosol mass concentration in $\mu g m^{-3}$. The constant C_{ccn} in the equation (7) is replaced by the spatially and temporally varying C_{ccn} values, derived from equation (8), using the sulfate aerosol mass concentration from the

15 MUSCAT module. Even though, this empirical relationship that links sulfate aerosol mass concentration to C_{ccn} are widely used is subject to substantial uncertainty. Representing sulfate aerosol as surrogate for all aerosols is probably too simple to capture the complexity of the whole activation process.

2.2 Model evaluation method

- Satellite retrievals have been used to evaluate performance of the numerous GCMs and NWP models (Quaas et al., 2004,
- 20 2009; Zhang et al., 2005; Brunke et al., 2010; Cherian et al., 2012; Nam et al., 2014). However, a meaningful evaluation of modeling with satellite observations is challenging because of the difference in the model variables and the satellite retrievals. To address this problem, the integrated satellite simulator COSP (CFMIP Observational Simulator Package, Bodas-Salcedo et al., 2011) has been developed within the framework of Cloud Feedback Model Intercomparison Project (CFMIP). The COSP satellite simulator produces model diagnostics, which are fully consistent to satellite products such as, International Satellite
- 25 Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999), MODerate Resolution Imaging Spectroradiometer (MODIS; Platnick et al., 2003; Pincus et al., 2012), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; Chepfer et al., 2010) and the CloudSat cloud radar (Marchand et al., 2009). ***To produce similar output to satellite data, COSP requires grid mean vertical profile of temperature, humidity, hydrometer mixing ratio, cloud optical thickness and emissivity, surface temperature and emissivity from the model. It produces the output comparable with satellite data in three steps. First***
- 30 ***it addresses the miss match between model and satellite pixel, second vertical profiles of individual sub-columns are passed***

to each instruments and finally COSP statistic module gathers the output from all instruments (Bodas-Salcedo et al., 2011). Since COSP is running online with COSMO model, it is able produce output similar to model simulation (in every hour). An important aspect of COSP satellite simulator is positional errors due to mismatch between meteorological regimes in the observation and models, which is not considered. This tool has previously been used with COSMO by Muhlbauer et al. (2014, 5 2015). The diagnostics include a variety of cloud properties, which enables consistent inter-model and model-to-observation comparisons. In spite of COSP satellite products, CERES [Clouds and the Earth's Radiant Energy System, Loeb et al. (2012)] satellite observations are also used for model evaluations. One should keep in mind that the satellite products, just like models, are prone to biases. Comparisons of satellite retrievals with in-situ measurements have shown overestimation. Nonetheless, spatial correlation of the cloud structures are well represented (Noble and Hudson, 2015; Min et al., 2012). In 10 the next step, we evaluate the model results in terms of cloud optical and microphysical properties with MODIS level-2 data sets. In the two model versions (COSMO2MR and COSMO-MUSCAT), we make use of the MODIS simulator diagnostics. The different swath data sets of MODIS level-2 on 17 February 2007 (day time overpass only) are combined and gridded to the model domain. To reduce the uncertainty in cloud phase, MODIS (Terra) level-2 products and model simulations are screened for liquid phase clouds only. Additionally, MODIS cloud optical depth and effective radius are applied with 15 threshold values of 5 and $2\mu m$ (Sourdeval et al., 2016; Zhang et al., 2012). Further, the COSP-diagnosed model clouds are compared to ISCCP daily cloud products. To compare with ISCCP satellite retrievals, model results are re-gridded from 28 km to 280 km resolution, using a grid interpolation method and model outputs are daily averaged.

3 Results for a case study

The simulations are carried out for a time period of 10 days (15 - 25 February 2007). The weather is evidently a complex 20 processes which exhibits lots of variations. As forecast time progress the uncertainty in weather prediction also increases. Hence, we have considered third day of the simulation for validating model and satellite simulators. Moreover, the synoptic conditions are favorable for comparisons, which discussed in the next section. To isolate and analyse the effects of the modifications, three different simulations were carried out, (a) COSMO two-moment (COSMO-2M), with fixed CCN ($3.0 \times 10^8 m^{-3}$), (b) COSMO two-moment with radiation coupled to microphysics (COSMO-2MR), with fixed CCN ($3.0 \times 10^8 m^{-3}$), 25 which uses equation 3 to 5 in radiation scheme, and (c) coupled simulation, i.e. using interactive rather than prescribed CCN concentrations (COSMO-MUSCAT). In most of the discussion we have used simulations (a) and (c).

3.1 Synoptic situation

The simulation starts on 15 February and ends on 25 February 2007. At the beginning of the simulation the meteorological condition is dominant by low pressure system over north Atlantic and high pressure systems over the land. The 2-m 30 temperature still shows temperature gradient with warm ocean and a cool continent, mostly in the northeastern part of the domain. The winds are mostly strong southwesterly over the Atlantic and northerly and northwesterly in the southern region as well (Figure S1). Since the case study has been conducted for 17 February, the key meteorological parameters,

are illustrated in Figure 2. On February 17, the low pressure system has been moved to the French Atlantic coast and a cyclonic circulation has been setup over the region. Further, a strong high pressure can be noticed over northeastern Europe. The 2-m temperature shows that, still the prominent winter synoptic condition exist in the northern part with warm oceanic region (Atlantic) and cold northeastern part. The southern region has a maximum temperature of 20°C , whereas the northeastern continental region experiences a minimum temperature of -20°C . The cyclonic circulation drives the airmass from the oceanic region and results in the formation of clouds along the cyclonic circulation. Besides, the airmass from the high pressure results in cloud free region in the middle of the domain. However, most of the domain is covered with a cloud fraction close to 100%. Further, the total amount of rainfall on 17 February is observed along with the cyclonic circulation and south eastern part of Europe, with highest value over south of the low pressure system, which is 100 kgm^3 . The convective cloud bases are observed between 500 to 4000 m over the domain.

3.2 Evaluation with satellite data

The model derived cloud fraction is daily averaged to illustrate the comparison between model (COSP) and ISCCP satellite retrievals (Figure 3). The observed cloud fraction shows more cloud free regions compared to model simulations. *This may arise due to the coarse (280 km resolution) resolution of the satellite observation or poor parameterization of clouds in the model.* Nevertheless, it is evident that the model derived cloud fraction is in broad agreement with ISCCP satellite retrievals, allowing now for a more detailed analysis of the cloud microphysical properties with fine resolution that are at the center of this study. Further, flux comparison with CERES (Clouds and the Earth's Radiant Energy System) satellite products are discussed in section 3.3.

Figure 4 shows the comparison between MODIS observed and model simulated (averaged between 8.00 -14.00 UTC, COSP) cloud optical depth, cloud droplet effective radius, and cloud liquid water path, respectively. In general, we find that the simulated cloud optical depth exhibits a spatial pattern similar to the observations, with a higher magnitude in MODIS level-2 retrievals (Figure 4a and d). *In satellite, it varies between 5 to 54 and in model between 5 to 45, with maximum values observed over similar geographical regions. However, the satellite derived cloud optical depth and liquid water path are overestimated while comparing with model (COSMO-MUSCAT) outputs.* Although the model derived cloud effective radius is underestimated compared to MODIS data, both exhibit a similar spatial pattern (Figure 4b and e). The model cloud droplet effective radius varies between 2 to $14\text{ }\mu\text{m}$, whereas it is in the range between 2 to $20\text{ }\mu\text{m}$ in the satellite retrievals. *The spatial pattern clearly indicates that, satellite derives cloud effective radius is overestimated, which may be due to the horizontal heterogeneity and it is specially visible in marine stratocumulus.* Also, note that MODIS possibly overestimate cloud droplet effective radius (Min et al., 2012; Noble and Hudson, 2015). The effect of marine stratocumulus is also visible in the case of observed MODIS cloud optical depth and cloud water path. Similar to cloud optical depth, cloud water path also exhibit comparable spatial patterns for both, model and observations. Its simulated magnitude also is in broad agreement with the satellite retrievals, with an underestimation in the model mainly over central eastern Europe and over the Atlantic coast. The cloud water path in both cases ranges between about 0.025 and 0.425 kgm^{-2} .

Even though, spatial distribution of satellite and model cloud microphysical properties can be compared and validated, however, absolute comparison like spatial correlation and area mean can add uncertainty to the analysis. To overcome this, we have evaluated the statistical representation of cloud microphysical properties as probability density functions (PDFs) corresponding to model (COSMO-MUSCAT) and satellites, which can account for different resolution of model and satellite instruments (Figure 5). The solid lines in Figure 5 indicates, PDF for 17 February and the dashed line indicates for entire simulation period (15-24 February 20017). Figure 5 indicates that, in liquid water path, the model shows an overestimation in the lower range (below 0.08 kgm^{-2}) and underestimation above 0.08 kgm^{-2} , which is same for both cases (17 February and overall). For cloud optical depth, the model overestimate low clouds (optical depth below 10) and underestimate high clouds (above 20). In the case of cloud effective radius, overestimation is between 6 and $12 \mu\text{m}$ and underestimation above $12 \mu\text{m}$, which is same for both cases. This clearly indicates that, 17 February can be a representative for the entire simulation to compare with satellite observations.

The outcome of cloud microphysics modification is analyzed by considering the difference between the two simulations (COSMO-MUSCAT and COSMO2M), which is shown in Figure 4g, h, and i. The version considering the interactive aerosol number concentration (COSMO-MUSCAT) exhibits an increase in the cloud effective radius by a range of $1\text{-}4 \mu\text{m}$ throughout the domain, although a slight reduction can be noticed in a few areas. This indicates the impact of the activation and growth of the sulphate aerosol from MUSCAT model. In the case of cloud optical depth and cloud water path, both generally show an increases despite of reduction in a few areas. *The revised parameterization in coupled model has made modification in spatial distribution of cloud optical depth in the range of ± 15 and the liquid water exhibits a variation in the range of $\pm 0.12 \text{ kgm}^{-2}$. For the cloud droplet effective radius, the revised model version (COSMO-MUSCAT) better represented the retrieved distribution compared to other two variables. Additionally, analyzing the difference between COSMO2MR with COSMO2M accounts for the cloud mircophysics modification in COSMO-MUSCAT model.*

We have also included cloud droplet number concentration N_d as a diagnostics of the model via COSP satellite simulator (MODIS simulator in COSP). Figures 6a, b, and c show the spatial distribution of N_d for the COSMO-2M, COSMO-MUSCAT simulations and MODIS level-2 observations. From MODIS level-2 observations, cloud droplet number concentration N_d can be expressed in terms of cloud optical depth τ_c and effective radius r_e (Quaas et al., 2006), which is given by,

$$N_d = \alpha \tau_c^{0.5} r_e^{-2.5} \quad (9)$$

where $\alpha = 1.37 \times 10^{-5} \text{ m}^{-0.5}$. Uncertainty in derived N_d can arise from satellite droplet effective radius. As compared to COSMO-2M simulations, there is reduction in the COSMO-MUSCAT (using equation 9) N_d (Figure 6a and b), in which the cloud microphysics *are modified with interactive aerosols(COSMO-MUSCAT). Even though, satellite derived N_d values are overestimated, the spatial pattern is comparable with model simulations with N_d varies between 10 to 500 cm^{-3} . The underestimation of COSMO-MUSCAT N_d can be explained by cloud microphysics modification.* In the basic version of the COSMO-2M, the CCN is fixed as 300 cm^{-3} (for intermediate aerosol types), whereas the coupled model uses gridded CCN (Cloud Condensation Nuclei) information from the MUSCAT model. Figure 6d shows the vertically and daily averaged sulfate aerosol number concentration, which varies between 20 to 300 cm^{-3} . From figure 6d, maximum aerosol mass concentration

is observed over south eastern Europe. On the contrary, N_d shows less over the same region. This is because *Boucher and Lohmann* (1995) parameterization shows saturation of N_d over high aerosol or polluted regions (*Penner et al.*, 2001). Further, it may be difficult to correlate the spatial patterns of aerosol number concentration and cloud droplet number concentration because the droplet activation also controlled by several other meteorological properties, such as vertical velocity, microphysical links. However, model derived cloud optical properties strongly correlated.

While comparing modified two-moment scheme results with MODIS level-2 satellite products, the model shows more cloud free (clear) grid points. This indicates that model is unable to capture the sub grid scale cloud patterns accurately (Jason and Thomas, 2008), which may be due to the coarse resolution (0.25°) of the model. Further, the satellite retrieval (mainly thin clouds) are affected by snow cover, which could be rather ignored. The COSP satellite simulator derives the cloud information using specific cloud water content, ice content and snow content from cloud microphysical scheme. *Additionally, the model simulations via COSP is able to reproduce spatial patterns similar/comparable to that of satellite observations regardless of overestimation of satellite retrievals (MODIS), which are reported in previous studies.*

3.3 Impact on radiative balance

In addition, we have also implemented aerosol-cloud-radiation interactions in the COSMO model, by revising the radiation scheme in order to make use of a droplet-size-dependent cloud optical depth. Incorporating aerosol-cloud-radiation interactions in the model results in a significant change in the radiation fluxes. The analysis reveals an increase in shortwave wave flux distribution, which is in the order of 10 to 40 Wm^{-2} at the surface and 2 to 20 Wm^{-2} at top of the atmosphere. In turn, the long wave flux distribution shows an overall reduction in the range of -2 to -20 Wm^{-2} at the surface and top of the atmosphere. An exception in some increase (20 to 20 Wm^{-2}) at top of the atmosphere in *the northern part of the domain* (Figure 7). It is also noted that the cloud microphysics radiation coupling results in reduction in cloud optical properties, which would results more downward shortwave and upward longwave especially at the surface. *Further, the effect aerosol-cloud-radiation interaction seen to larger over ocean than over land, especially for surface net down short wave and long wave fluxes. The boundary effect in the difference can be ignored, which arises due to different physics in COSMO and GME.* In comparison with CERES [Clouds and the Earth's Radiant Energy System, *Loeb et al.* (2012)] satellite observations, the spatial pattern and the magnitude of model simulations are comparable with satellite observations, however the differences are neither systematic nor large (Figure 8). *Further, during winter the uncertainty in CERES flux observation are little higher (Guo et al., 2007). The difference in observed cloud optical properties (Figure 4) can also be attributed from impact of radiative balance.*

4 Conclusions

This paper discusses the modification of *Seifert and Beheng* (2006) two-moment scheme in COSMO model. This has been done with online-coupled MUSCAT model aerosol information, which allows for a microphysical aerosol effect on clouds. It has been achieved by replacing the constant cloud condensation nuclei profile in the COSMO two-moment scheme with gridded aerosol information derived from online-coupled MUSCAT model, using the *Boucher and Lohmann* (1995) parameterization,

which takes sulfate aerosol as a proxy. In addition the radiation scheme was revised to a droplet-size-dependent cloud optical depth, allowing now for aerosol-cloud-radiation interactions. In order to facilitate an evaluation using satellite retrievals, the COSP satellite simulator has been incorporated into the modeling system, which runs online with the model. The model results are evaluated with satellite observations from the ISCCP, MODIS, and CERES projects and instruments, respectively. Although

5 the two-moment cloud microphysics scheme in COSMO model has been modified, the model did not re-tuned to get reasonable 2m temperature or precipitation. The conclusions are summarized below.

1. The modified two-moment scheme results have been compared with two-moment version of COSMO model. In terms of the cloud distributions, this modification has only a minor effect.
2. A case study has been carried out to compare the model output with observations. Daily averaged cloud optical depth, droplet
- 10 effective radius, and liquid water path are compared with MODIS level-2 products. ***The interactive treatment of aerosols in COSMO-MUSCAT simulations show an improvement in the cloud microphysical properties. Further, the PDF analysis has contributed to a quantitative comparison of model results with satellite observations.*** The cloud effective radius exhibits an increase and the cloud droplet number concentration shows a reduction in the modified simulation. This is due to the reduced CCN number concentrations from the MUSCAT model. The satellite retrievals suggest the revised model version is
- 15 more realistic in both quantities.
3. The representation of cloud microphysical properties in the radiation scheme has been revised in order to digest the additional information about cloud particle sizes the two-moment microphysics scheme offers. Again, considerable changes in terms of the radiation budget were also found. The new approach now, however, allows to explicitly take into account the radiative effects of aerosol-cloud interactions.
- 20 In next step, further improvement in two-moment scheme will be carried out through use of the newly included aerosol model M7 (Vignati *et al.*, 2004) framework in the MUSCAT model, which is able to provide aerosol number concentration information to the COSMO two-moment scheme by replacing Boucher and Lohmann (1995) parameterization. ***This can result in more precise cloud droplet activation parameterization, involving different aerosol species as CCN, and thus improving the cloud droplet number calculation of (Lohmann *et al.*, 2007). Also the role of aerosols on ice nucleation will be addressed.***

25

Code and data availability

The COSMO-MUSCAT(5.0) model is freely available under public license policy. The source code, external parameters and documentation can be obtained through Ralf Wolke (wolke@tropos.de).

Acknowledgements. This work was supported by an ERC starting grant “QUAERERE” (GA no 306284). We acknowledge the development

30 work by the COSMO consortium. We thank Axel Seifert for valuable suggestions.

References

- Ackerman, A. S., O. B. Toon, D. E. Stevens, A. J. Heymsfield, V. Ramanathan, and E. J. Welton, (2000), Reduction of tropical cloudiness by soot, *Science*, 288, 1042-1047, doi:10.1126/science.288.5468.1042.
- Ackerman, A. S., M. P. Kirkpatrick, D. E. Stevens, and O. B. Toon, (2004), The impact of humidity above stratiform clouds on indirect aerosol climate forcing, *Nature*, 432, 1014-1017, doi:10.1038/nature03174.
- Baldauf, M., A. Seifert, J. Förstner, D. Majewski, M. Raschendorfer, T. Reinhardt, (2011), Operational convective-scale numerical weather prediction with the COSMO Model: Description and sensitivities, *Mon. Wea. Rev.*, 139, 3887-3905.
- Bangert, M., Kottmeier, C., Vogel, B., and Vogel, H., (2011), Regional scale effects of the aerosol cloud interaction simulated with an online coupled comprehensive chemistry model, *Atmos. Chem. Phys.*, 11, 4411-4423, doi:10.5194/acp-11-4411-2011.
- Beheng, K. D., G. Doms, (1986), A general formulation of collection rates of clouds and raindrops using the kinetic equation and comparison with parameterizations, *Contrib. Atmos. Phys.* 59, 66-84.
- Berner, A. H., Bretherton, C. S., Wood, R., and Muhlbauer, A., (2013), Marine boundary layer cloud regimes and POC formation in a CRM coupled to a bulk aerosol scheme, *Atmos. Chem. Phys.*, 13, 12549-12572, doi:10.5194/acp-13-12549-2013.
- Bodas-Salcedo, A., and Coauthors, (2011), COSP: Satellite simulator software for model assessment, *Bull. Amer. Meteor. Soc.*, 92, 1023-1043.
- Bodas-Salcedo, A., M. J. Webb, M. E. Brooks, M. A. Ringer, K. D. William, S. F. Milton, and D. R. Wilson (2008), Evaluating cloud systems in the Met Office global forecast model using simulated CloudSat radar reflectivities, *J. Geophys. Res.*, 113, D00A13, doi:10.1029/2007JD009620.
- Boucher, O., and U. Lohmann, (1995), The sulfate-CCN-cloud albedo effect: A sensitivity study with two general circulation models, *Tellus*, 47 Ser. B, 281-300.
- Brunke, M. A., S. P. de Szoek, P. Zuidema, and X. Zeng, (2010), A comparison of ship and satellite measurements of cloud properties with global climate model simulations in the southeast Pacific stratus deck, *Atmos. Chem. Phys.*, 10, 6527-6536.
- Chepfer, H., S. Bony, D. Winker, G. Cesana, J. L. Dufresne, P. Minnis, C. J. Stubenrauch, and S. Zeng, (2010), The GCM oriented CALIPSO cloud product (CALIPSO-GOCCP), *J. Geophys. Res.*, 115, D00H16, doi:10.1029/2009JD012251.
- Chapman, E. G. and Gustafson Jr., W. I. and Easter, R. C. and Barnard, J. C. and Ghan, S. J. and Pekour, M. S. and Fast, J. D., (2009), Coupling aerosol-cloud-radiative processes in the WRF-Chem model: Investigating the radiative impact of elevated point sources, *Atmos. Chem. Phys.*, 9, 945-964, doi:10.5194/acp-9-945-2009.
- Cherian, R., C. Venkataraman, S. Ramachandran, J. Quaas, and S. Kedia, (2012), Examination of aerosol distributions and radiative effects over the Bay of Bengal and the Arabian Sea region during ICARB using satellite data and a general circulation model, *Atmos. Chem. Phys.*, 12, 1287-1305, doi:10.5194/acp-12-1287-2012.
- Cotton, W. R., G. P. Tripoli, R. M. Rauber, E. A. Mulvihill, (1986) Numerical simulation of the effects of varying ice crystal nucleation rates and aggregation processes on orographic snowfall, *J. Clim. Appl. Meteorol.*, 25, 1658-1680.
- Doms, G. and U. Schättler, (1999), The Nonhydrostatic Limited-Area Model LM (Lokal-Modell) of DWD: Part I: *Scientific Documentation (Version LM-F90 1.35)*, Deutscher Wetterdienst, Offenbach.
- Forkel R., A. Balzarini, R. Baró, R. Bianconi, G. Curci, P. Jiménez-Guerrero, M. Hirtl, L. Honzak, C. Lorenz, Ulas Im, J. L. Pérez, G. Pirovano, R. S. José, P. Tuccella, J. Werhahn, R. Žabkar, (2015), Analysis of the WRF-Chem contributions to AQMEII

- 35 phase2 with respect to aerosol radiative feedbacks on meteorology and pollutant distributions, *Atmos. Environ.*, *115*, 630-645, <http://dx.doi.org/10.1016/j.atmosenv.2014.10.056>.
- Ghan, S., M. Wang, S. Zhang, S. Ferrachat, A. Gettelman, J. Griesfeller, Z. Kipling, U. Lohmann, H. Morrison, D. Neubauer, D. G. Partridge, P. Stier, T. Takemura, H. Wang, and K. Zhang, (2016), Challenges in constraining anthropogenic aerosol effects on cloud radiative forcing using present-day spatiotemporal variability, *Proc. Nat. Acad. Sci. USA*, doi:10.1073/pnas.1514036113.
- IPCC, 2013: Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, 1535 pp, doi:10.1017/CBO9781107415324.
- 5 Jason, A., O., and Thomas J. Greenwald, (2008), Comparison of WRF model simulated and MODIS derived cloud data, *Mon. Wea. Rev.*, *136*, 1957-1970.
- 10 Guo, S., L. Henry, and M. Murray, (2007), Surface-Absorbed and Top-of-Atmosphere Radiation Fluxes for the Mackenzie River Basin from Satellite Observations and a Regional Climate Model and an Evaluation of the Model, *Canadian Meteorological & Oceanographic Society*, v. *45*, no. *3*, p. 129-139.
- Kessler, E., (1969), On the distribution and continuity of water substance in atmospheric circulations, *Atmos. Res.*, *38*, 109-145, doi:10.1016/0169-8095(94)00090-Z.
- 15 Khain, A., M. Ovtchinnikov, M. Pinsky, A. Pokrovsky, H. Krugliak, (2000), Notes on the state-of-the-art numerical modeling of cloud microphysics, *Atmos. Res.*, *55*, 159 - 224.
- Khain A. P., D. Rosenfeld, A. Pokrovsky, (2001), Simulating convective clouds with sustained supercooled liquid water down to 37.5 oC using a spectral microphysics model, *Geophys Res. Lett.* *28*, 3887-3890
- Li, G., Y. Wang, and R. Zhang, (2008), Implementation of a two-moment bulk microphysics scheme to the WRF model to investigate aerosol-cloud interaction, *J. Geophys. Res.*, *113*, D15211
- 20 Lim, K. Sunny, S. Hong, (2010), Development of an Effective Double-Moment Cloud Microphysics Scheme with Prognostic Cloud Condensation Nuclei (CCN) for Weather and Climate Models, *Mon. Wea. Rev.*, *138*, 1587-1612.
- Lin, Y. -L., R. D. Farley, H. Orville, (1983), Bulk parameterization of the snow field in a cloud model, *J. Clim. Appl. Meteorol.*, *22*, 1065-1092.
- Loeb, N. G., J. M. Lyman, G. C. Johnson, R. P. Allan, D. R. Doelling, T. Wong, . J. Soden, and G. L. Stephens, (2012), Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty, *Nature Geosci.* *5*, 110-113, doi:10.1038/ngeo1375.
- 25 Lohmann, U., Stier, P., Hoose, C., Ferrachat, S., Kloster, S., Roeckner, E., and Zhang, J., (2007), Cloud microphysics and aerosol indirect effects in the global climate model ECHAM5-HAM, *Atmos. Chem. Phys.*, *7*, 3425-3446.
- Majewski, D., D. Liermann, P. Prohl, B. Ritter, M. Buchhold, T. Hanisch, G. Paul, W. Wergen, and J. Baumgardner, (2002) The operational global Icosahedral-Hexagonal Gridpoint Model GME: description and high-resolution tests, *J. Atmos. Sci.*, *139*, 319-338.
- 30 Marchand, R., J. Haynes, G. G. Mace, T. Ackerman, and G. Stephens (2009), A comparison of simulated cloud radar output from the multiscale modeling framework global climate model with CloudSat cloud radar observations, *J. Geophys. Res.*, *114*, D00A20, doi:10.1029/2008JD009790.
- Martin, G. M., D. W. Johnson, and A. Spice, (1994), The measurement and parameterization of effective radius of droplets in the warm stratocumulus clouds, *J. Atmos. Sci.*, *51*, 1823-1842.
- 35 Meyers, M. P., R. L. Walko, J. Y. Harrington, W. R. Cotton, (1997), New RAMS cloud microphysics parameterization: Part II. The two-moment scheme, *Atmos. Res.* *45*, 3-39.

- Min, Q., Joseph, E., Lin, Y., Min, L., Yin, B., Daum, P. H., Kleinman, L. I., Wang, J., and Lee, Y.-N., (2012), Comparison of MODIS cloud microphysical properties with in-situ measurements over the Southeast Pacific, *Atmos. Chem. Phys.*, *12*, 11261-11273, doi:10.5194/acp-12-11261-2012.
- Morrison, H., A. Gettelman, (2008), A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, Version 3 (CAM3). Part I: Description and numerical tests, *J. Climate*, *21*, 3642-3659.
- Morrison, H., G. Thompson, V. Tatarskii, (2009), Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of One- and two-moment schemes, *Mon. Wea. Rev.*, *137*, 991-1007.
- 5 Muhlbauer, A., T. P. Ackerman, R. P. Lawson, S. Xie, and Y. Zhang (2015), Evaluation of cloud-resolving model simulations of midlatitude cirrus with ARM and A-train observations, *J. Geophys. Res. Atmos.*, *120*, 6597-6618. doi: 10.1002/2014JD022570.
- Muhlbauer, A., E. Berry, J. M. Comstock, and G. G. Mace (2014), Perturbed physics ensemble simulations of cirrus on the cloud system-resolving scale, *J. Geophys. Res. Atmos.*, *119*, 4709-4735, doi:10.1002/2013JD020709.
- 10 Nam, C., J. Quaas, R. Neggers, C. Siegenthaler-Le Drian, and F. Isotta, (2014), Evaluation of boundary layer cloud parameterizations in the ECHAM5 general circulation model using CALIPSO and CloudSat satellite data, *J. Adv. Model. Earth Syst.*, *6*, 300-314, doi:10.1002/2013MS000277.
- Nam, C., and J. Quaas, (2012), Evaluation of clouds and precipitation in the ECHAM5 general circulation model using CALIPSO and CloudSat, *J. Clim.*, *25*, 4975-4992, doi:10.1175/JCLI-D-11-00347.1.
- 15 Noble, S. R., and J. G. Hudson (2015), MODIS comparisons with northeastern Pacific in situ stratocumulus microphysics, *J. Geophys. Res. Atmos.*, *120*, 8332-8344, doi:10.1002/2014JD022785.
- Penner, J. E., Andreae, M., Annegarn, H., Barrie, L., Feichter, J., Hegg, D., Jayaraman, Leaitch, R., Murphy, D., Nganga, J., and Pitari, G.: Aerosols, their Direct and Indirect Effects, in: Climate Change 2001: The Scientific Basis, Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., *Cambridge Univ. Press, New York*, 881.
- 20 Penner, J. E. and Quaas, J. and Storelvmo, T. and Takemura, T. and Boucher, O. and Guo, H. and Kirkevåg, A. and Kristjánsson, J. E. and Seland, Ø., (2006), Model intercomparison of indirect aerosol effects, *Atmos. Chem. Phys.*, *6*, 11, 3391-3405.
- Pincus, R., S. Platnick, S. A. Ackerman, R. S. Hemler, and R. J. P. Hofmann, (2012), Reconciling simulated and observed views of clouds: MODIS, ISCCP, and the limits of instrument simulators, *J. Climate*, *25*, 4699-4720. doi:10.1175/JCLI-D-11-00267.1
- 25 Platnick, S., King, M. D., Ackerman, S. A., Menzel, W. P., Baum, B. A., Riedi, J. C., and Frey, R. A., (2003) The MODIS cloud products: Algorithms and examples from Terra, *IEEE Trans. Geosci. Remot. Sens.*, *41*, 459-473.
- Pouliot, G., Pierce, T., Denier van der Gon, H., Schaap, M., Moran, M., Nopmongkol, U., (2012), Comparing emissions inventories and model-ready emissions datasets between Europe and North America for the AQMEII project, *Atmos. Environ.*, *53*, 4e14.
- Possner, A., Zubler, E., Lohmann, U., and Schär, C., (2015), Real-case simulations of aerosol-cloud interactions in ship tracks over the Bay of Biscay, *Atmos. Chem. Phys.*, *15*, 2185-2201, doi:10.5194/acp-15-2185-2015.
- 30 Quaas, J., Y. Ming, S. Menon, T. Takemura, M. Wang, J. Penner, A. Gettelman, U. Lohmann, N. Bellouin, O. Boucher, A. M. Sayer, G. E. Thomas, A. McComiskey, G. Feingold, C. Hoose, J. E. Kristjánsson, X. Liu, Y. Balkanski, L. J. Donner, P. A. Ginoux, P. Stier, B. Grandey, J. Feichter, I. Sednev, S. E. Bauer, D. Koch, R. G. Grainger, A. Kirkevåg, T. Iversen, Ø. Seland, R. Easter, S. J. Ghan, P. J. Rasch, H. Morrison, J. -F. Lamarque, M. J. Iacono, S. Kinne, and M. Schulz, (2009), Aerosol indirect effects - general circulation model intercomparison and evaluation with satellite data, *Atmos. Chem. Phys.*, *9*, 8697-8717, doi:10.5194/acp-9-8697-2009.
- 35

- Quaas, J., O. Boucher, and F. -M. Bréon, (2004), Aerosol indirect effects in POLDER satellite data and in the Laboratoire de Météorologie Dynamique-Zoom (LMDZ) general circulation model, *J. Geophys. Res.*, *109*, D08205, doi:10.1029/2003JD004317.
- Quaas, J., O. Boucher, and U. Lohmann, (2006), Constraining the total aerosol indirect effect in the LMDZ and ECHAM4 GCMs using MODIS satellite data, *Atmos. Chem. Phys.*, *6*, 947-955, doi:10.5194/acp-6-947-2006.
- Reisner, J., R. M. Rasmussen, R. T. Bruintjes, (1998), Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model, *Q. J. Royal Meteorol. Soc.* *124*, 1071-1107.
- 5 Renner, E., R. Wolke, (2010), Modelling the formation and atmospheric transport of secondary inorganic aerosols with special attention to regions with high ammonia emissions, *Atmos. Environ.*, *44*, 1904-912.
- Ritter, B., and J. Geleyn, (1992), A comprehensive Radiation scheme for numerical weather prediction models with potential applications in climate simulations, *Mon. Wea. Rev.*, *120*, 303-325.
- Rossow, W. B., and R. A. Schiffer, (1999), Advances in understanding clouds from ISCCP, *Bull. Amer. Meteorol. Soc.*, *80*, 2261-2288, doi:10.1175/1520-0477(1999)080<2261:AIUCFI>2.0.CO;2.
- 10 Sandu, I., J. L. Brenguier, O. Geoffroy, O. Thoueron and V. Masson, (2008), Aerosols impacts on the diurnal cycle of marine stratocumulus, *J. Atmos. Sci.* *65*, 2705-2718.
- Seifert, A., T. Heus, R. Pincus, and B. Stevens (2015), Large-eddy simulation of the transient and near-equilibrium behavior of precipitating shallow convection, *J. Adv. Model. Earth Syst.*, *7*, 1918-1937, doi:10.1002/2015MS000489.
- 15 Seifert, A., C. Köhler, and K. D. Beheng, (2012), Aerosol-cloud-precipitation effects over Germany as simulated by a convective-scale numerical weather prediction model, *Atmos. Chem. Phys.*, *12*, 709-725.
- Seifert, A. and K. D. Beheng, (2006) A two-moment cloud microphysics parameterization for mixed- phase clouds. Part 1: Model description, *Meteorol. Atmos. Phys.*, *92*, 45-66.
- Seifert, A. and K. D. Beheng, (2001), A double-moment parameterization for simulating autoconversion, accretion and selfcollection, *Atmos. Res.*, *59-60*, 265-281.
- 20 Simmel, M., Bühl, J., Ansmann, A., and Tegen, I., (2015), Ice phase in altocumulus clouds over Leipzig: remote sensing observations and detailed modeling, *Atmos. Chem. Phys.*, *15*, 10453-10470, doi:10.5194/acp-15-10453-2015.
- Steppeler, J., G. Doms, U. Schüttler, H. W. Bitzer, A. Gassmann, U. Damrath, Gregoric (2003), Meso-gamma scale forecasts using the nonhydrostatic model LM, *Met. Atmos. Phys.*, *82*, 75-96.
- 25 Stevens Bjorn and Feingold Graham (2009), Untangling aerosol effects on clouds and precipitation in a buffered system, *Nature*, *7264*, 607-613.
- Stockwell, W.R., Kirchner, F., Kuhn, M., Seefeld, S., (1997), A new mechanism for regional atmospheric chemistry modeling, *J. Geophys. Res.*, *102*, (D22), 25847-25879.
- Sourdeval, O., C.-Labonnote, L., Baran, A. J., Mülmenstädt, J. and Brogniez, G. (2016), A methodology for simultaneous retrieval of ice and liquid water cloud properties. Part 2: Near-global retrievals and evaluation against A-Train products. *Q.J.R. Meteorol. Soc.*, *142*, 3063-3081. doi:10.1002/qj.2889
- 30 Tao, W.-K., J. Simpson, D. Baker, S. Braun, M.-D. Chou, B. Ferrier, D. Johnson, A. Khain, S. Lang, B. Lynn, C.-L. Shie, D. Starr, C.-H. Sui, Y. Wang and P. Wetzell, (2003), Microphysics, radiation and surface processes in the Goddard Cumulus Ensemble (GCE) model, *A Special issue on non-hydrostatic mesoscale modeling, meteorology and atmospheric physics*, *82*, 97-137.
- 35 Thompson, Gregory, P. I. R. Field, R. M. Rasmussen, W. D. Hall, (2008), Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. part II: Implementation of a new snow parameterization *Mon. Wea. Rev.*, *136*, 5095-5115.

- Vignati, E., J. Wilson and P. Stier, (2004), M7: An efficient size-resolved aerosol microphysics module for large-scale aerosol transport models, *J. Geophys. Res.* **109**, D22202.
- Van den Heever, Susan C. and Cotton, William R., (2007), Urban aerosol impacts on downwind convective storms, *J. of Appl. Meteor. Climatol.*, **46**, 828-850.
- Weverberg Van, K., E. Goudenhoofd, U. Blahak, E. Brisson, M. Demuzere, P. Marbaix, J. -P. van Ypersele, (2014), Comparison of one-moment and two-moment bulk microphysics for high-resolution climate simulations of intense precipitation, *Atmos. Res.*, **147-148**, 145-161.
- Wolke R., W. Schröder, R. Schrödner, E. Renner, (2012), Influence of grid resolution and meteorological forcing on simulated European air quality: a sensitivity study with the modeling system COSMO-MUSCAT, *Atmos. Environ.*, **53**, 110-130.
- Wolke, R., O. Knoth, O. Hellmuth, W. Schröder and E. Renner (2004), The parallel model system LM-MUSCAT for chemistry-transport simulations: Coupling scheme, parallelization and application, in: G. R. Joubert, W. E. Nagel, F. J. Peters, and W. V. Walter, Eds., *Parallel Computing: Software Technology, Algorithms, Architectures, and Applications*, Elsevier, Amsterdam, The Netherlands, 363-370.
- Xue, H., and G. Feingold, (2006), Large eddy simulations of trade-wind cumuli: Investigation of aerosol indirect effects, *J. Atmos. Sci.*, **63**, 1605 -1622.
- Yang, Q. and Gustafson Jr., W. I. and Fast, J. D. and Wang, H. and Easter, R. C. and Wang, M. and Ghan, S. J. and Berg, L. K. and Leung, L. R. and Morrison, H., (2012), Impact of natural and anthropogenic aerosols on stratocumulus and precipitation in the Southeast Pacific: a regional modelling study using WRF-Chem, *Atmos. Chem. Phys.*, **11**, 8777-8796, doi:10.5194/acp-12-8777-2012.
- Zhang, M. H., et al. (2005), Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements, *J. Geophys. Res.*, **110**, D15S02, doi:10.1029/2004JD005021.
- Zhang, Z., A. S. Ackerman, G. Feingold, S. Platnick, R. Pincus, and H. Xue (2012), Effects of cloud horizontal inhomogeneity and drizzle on remote sensing of cloud droplet effective radius: Case studies based on large-eddy simulations, *J. Geophys. Res.*, **117**, D19208, doi:10.1029/2012JD017655.
- Zubler, E. M., D. Folini, U. Lohmann, D. Lüthi, A. Mühlbauer, S. Pousse-Nottelmann, C. Schär, and M. Wild, (2011), Implementation and evaluation of aerosol and cloud microphysics in a regional climate model, *J. Geophys. Res.*, **116**, D02211, doi:10.1029/2010JD014572.

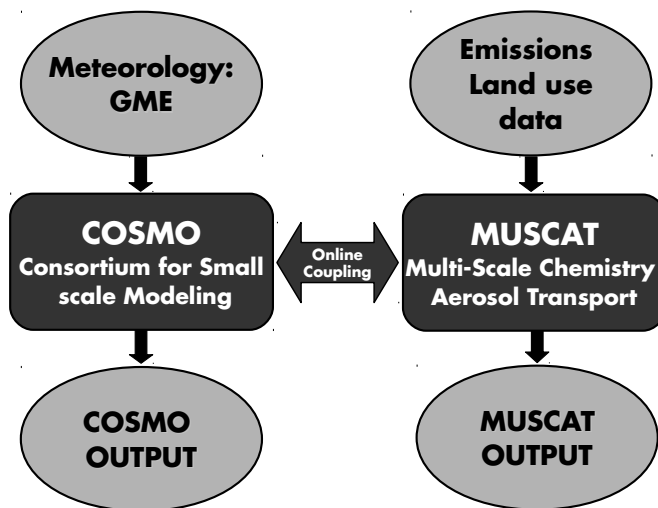


Figure 1. COSMO-MUSCAT modeling system. Lefthand side, setup of COSMO modeling sysytem with GME input and Righthand side: MUSCAT modeling system with land use and emissions.

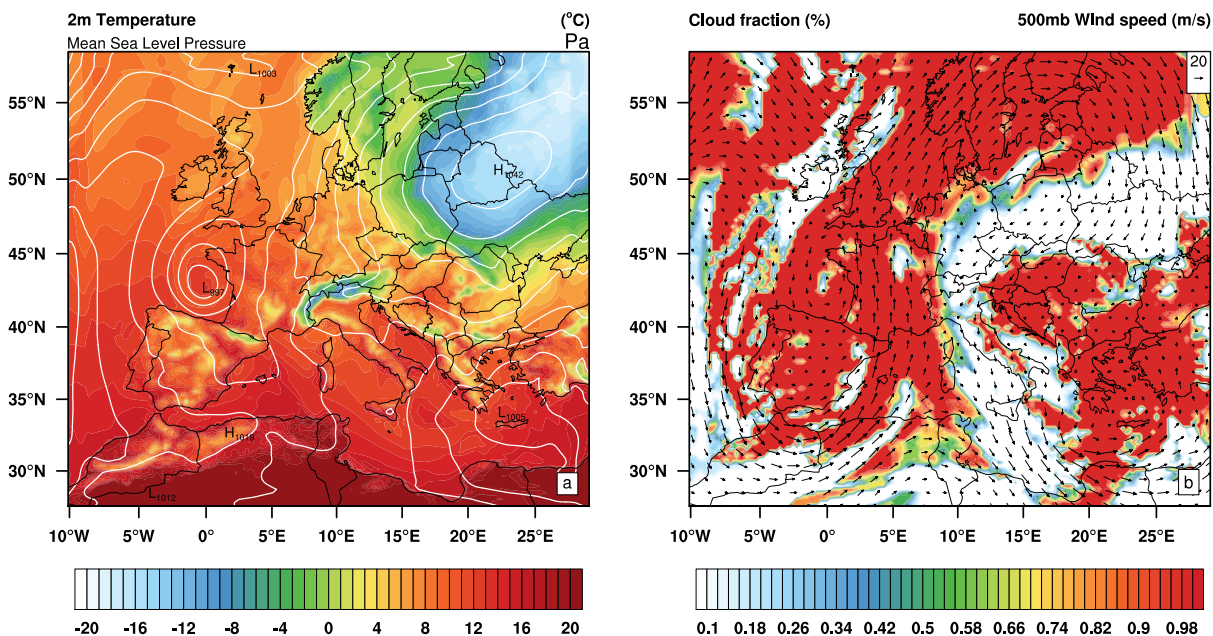


Figure 2. Model synoptic conditions for 17 February 2007 at 00:00hrs, (a) Surface pressure in contours and 2 meter temperature in closed contours, (b) 500 mb wind vector and total cloud area fraction.

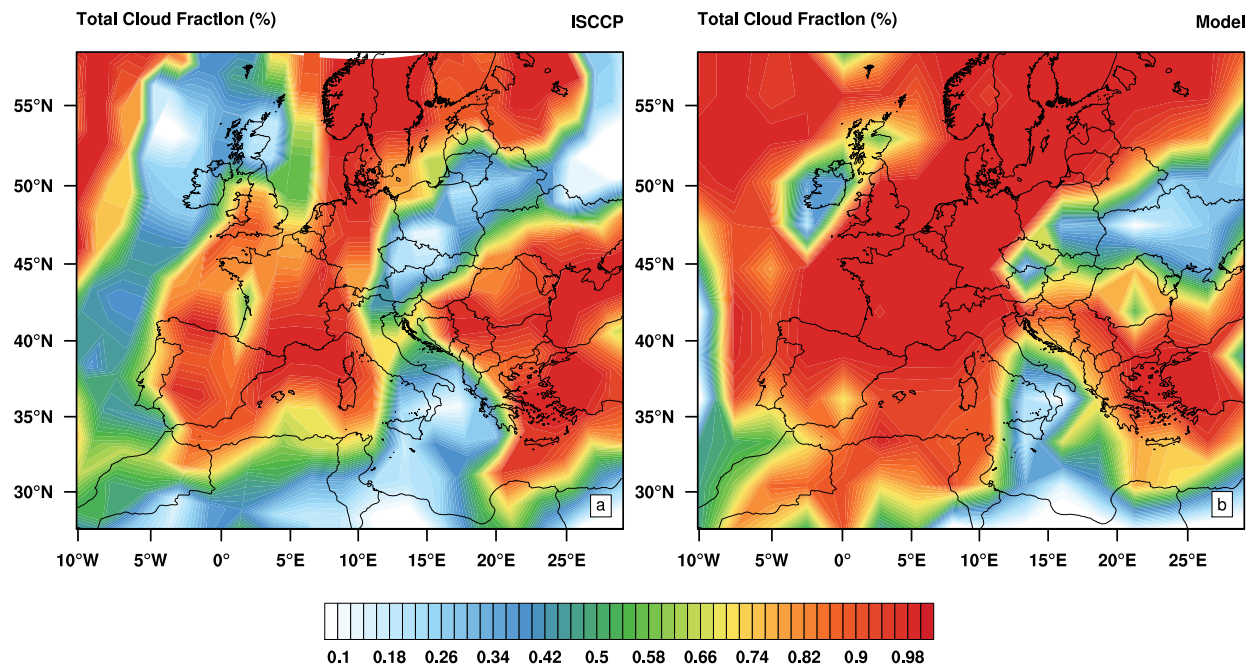


Figure 3. (a) Satellite and (b) model (COSMO-MUSCAT) derived ISCCP cloud fraction, for 17 February 2007 (daily averaged).

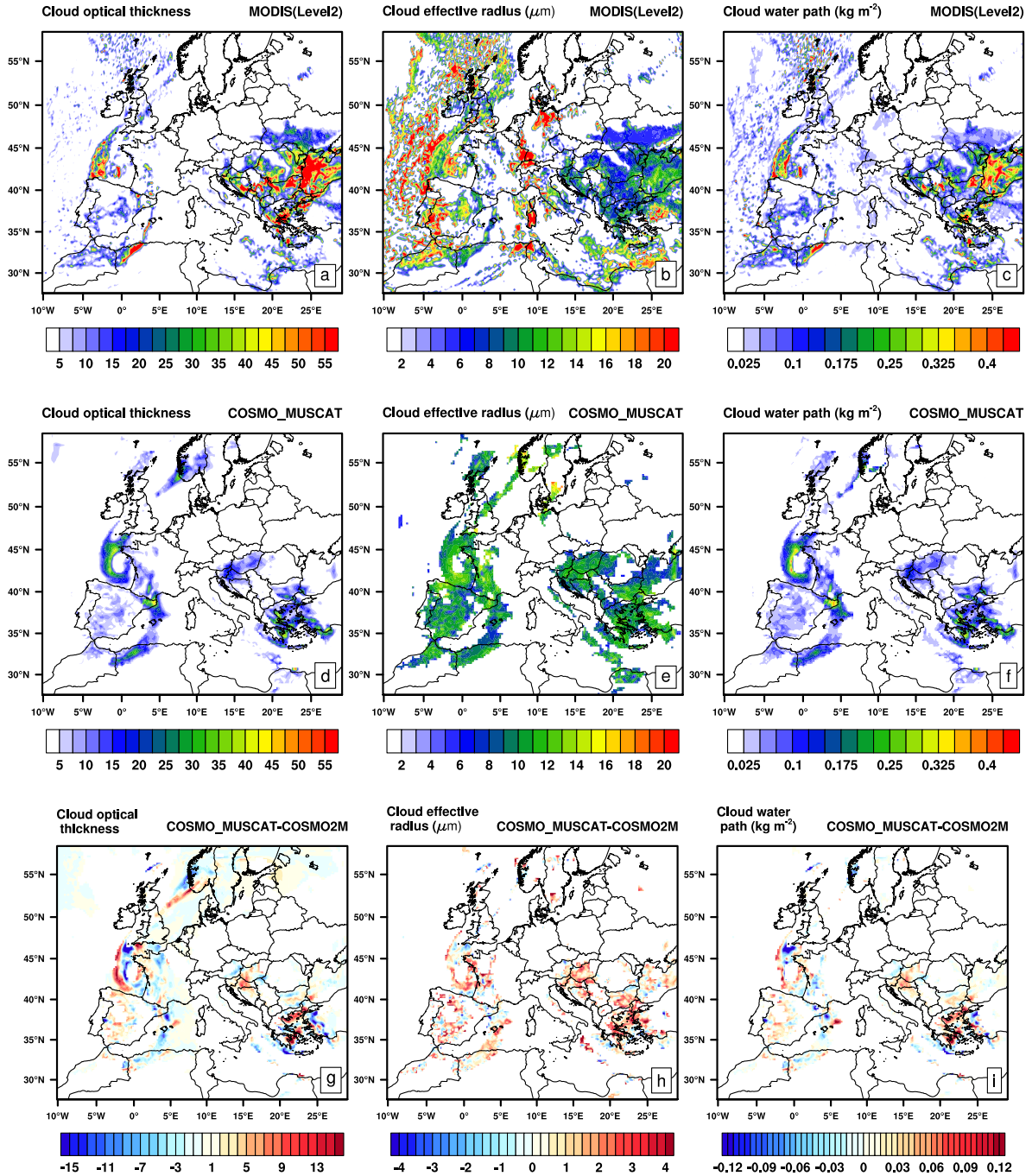


Figure 4. MODIS Level-2 (a) cloud optical depth, (b) cloud effective radius, (c) cloud water path, COSMO-MUSCAT derived (day time averaged) (d) cloud optical depth, (e) cloud effective radius, (f) cloud water path, and difference between COSMO-MUSCAT and COSMO-2M simulations(g,h,i), for 17 February 2007.

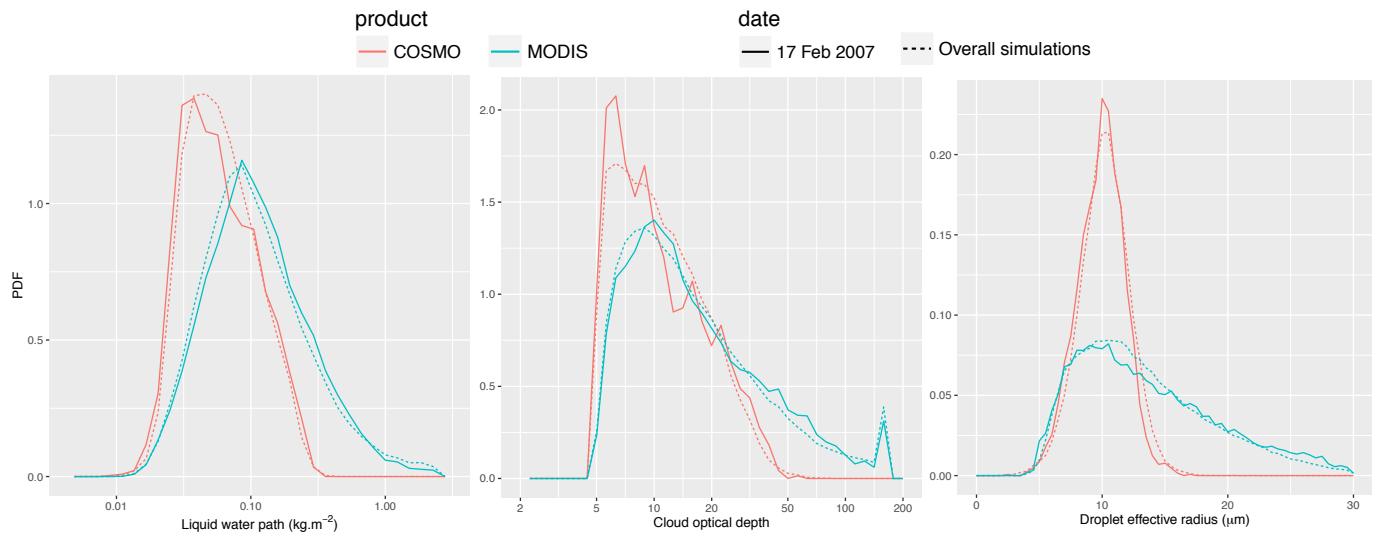


Figure 5. Probability density functions of cloud optical depth, cloud effective radius, cloud water path from COSMO-MUSCAT (red) and MODIS Level-2 products (green), for 17 February 2007 (solid line) and for entire (15-24 February 2007) simulation(dashed line).

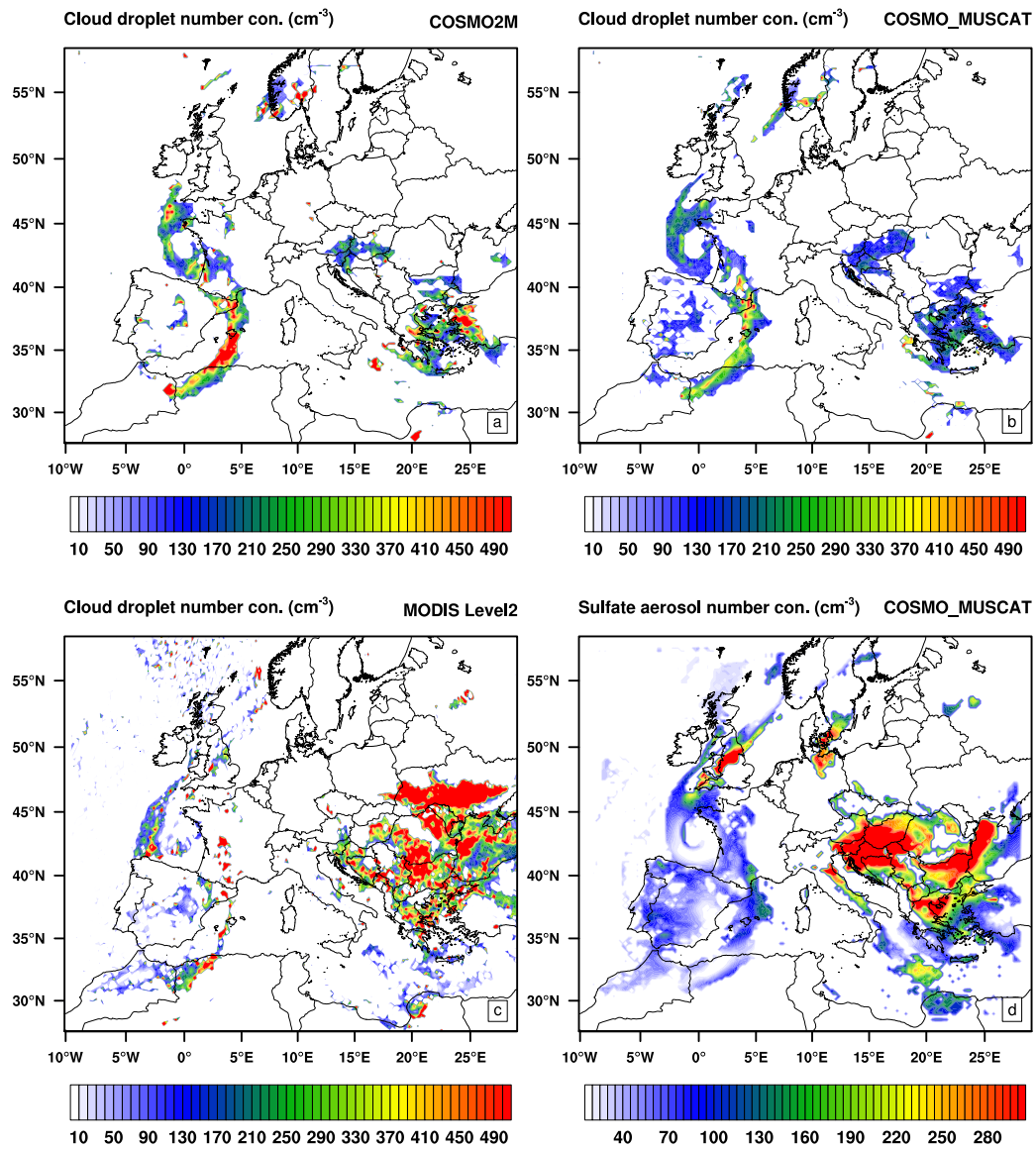


Figure 6. Day time averaged cloud droplet number concentration for (a) COSMO-2M, (b) COSMO-MUSCAT, (c)MODIS level-2 , and (d) Sulfate aerosol number concentration from MUSCAT model, for 17 February 2007.

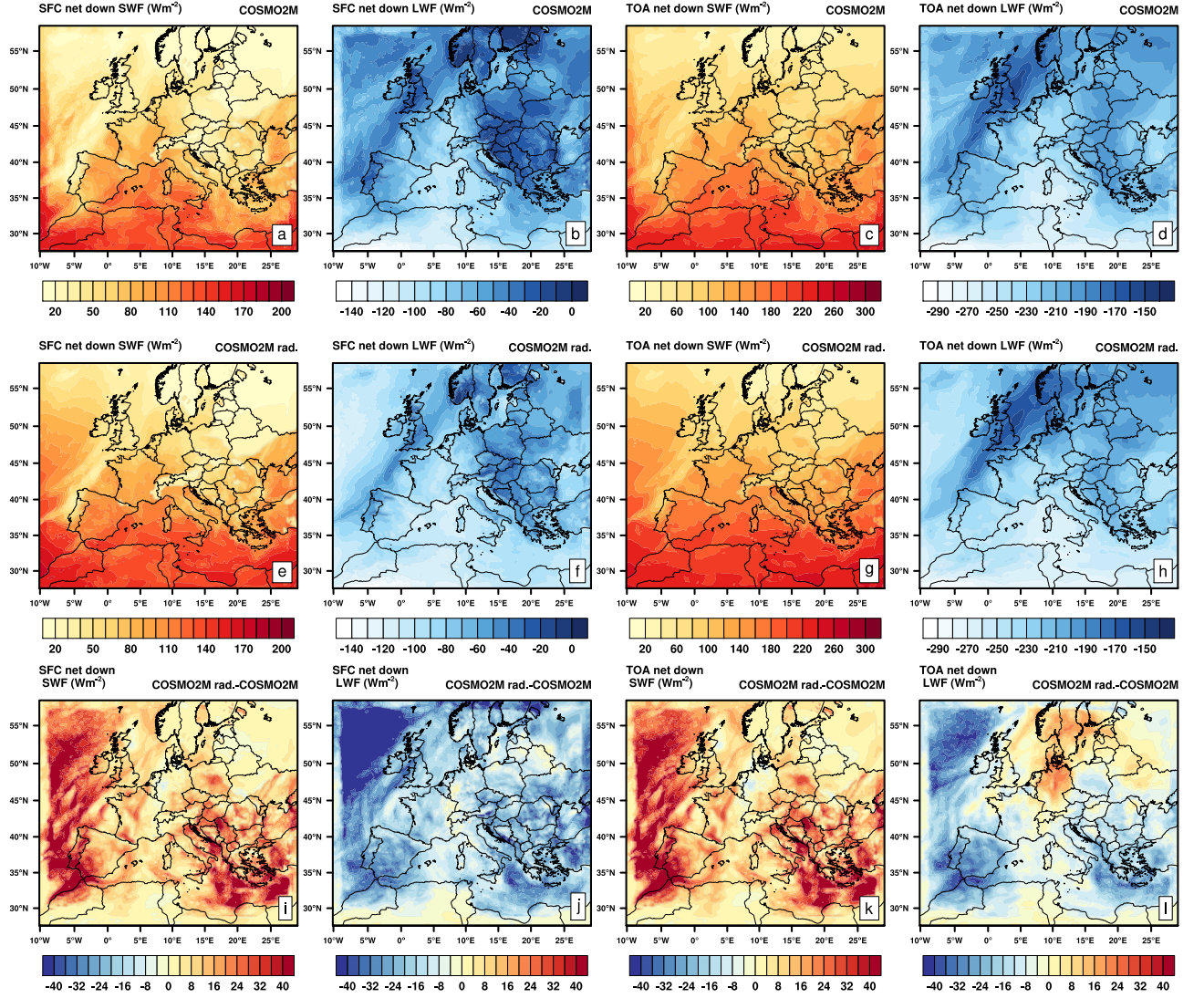


Figure 7. Comparison and difference between short wave and long wave radiation fluxes surface and top of the atmosphere, and its difference between two simulation (COSMO-2MR radiation coupled minus COSMO-2M).

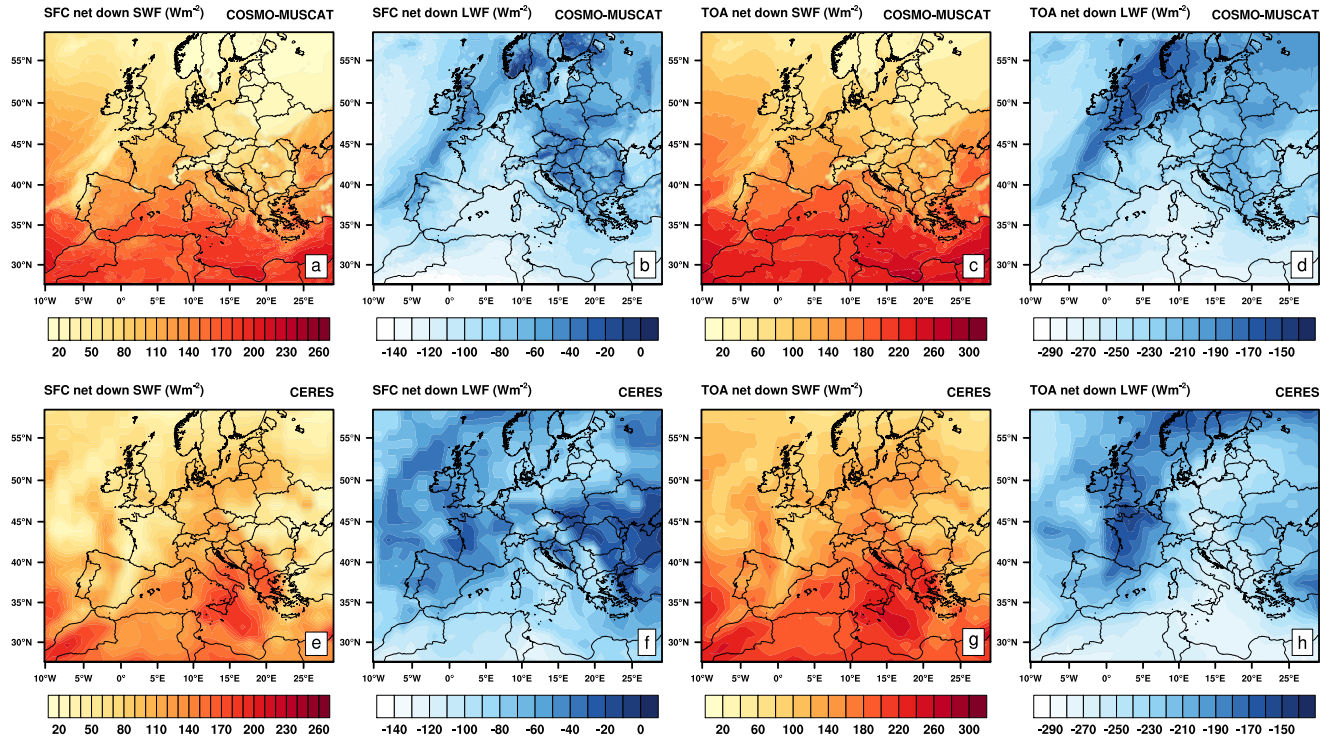


Figure 8. Comparison between short wave and long wave fluxes at surface and top of the atmosphere with CERES satellite fluxes (top panel: model COSMO-MUSCAT, bottom Panel: satellite).

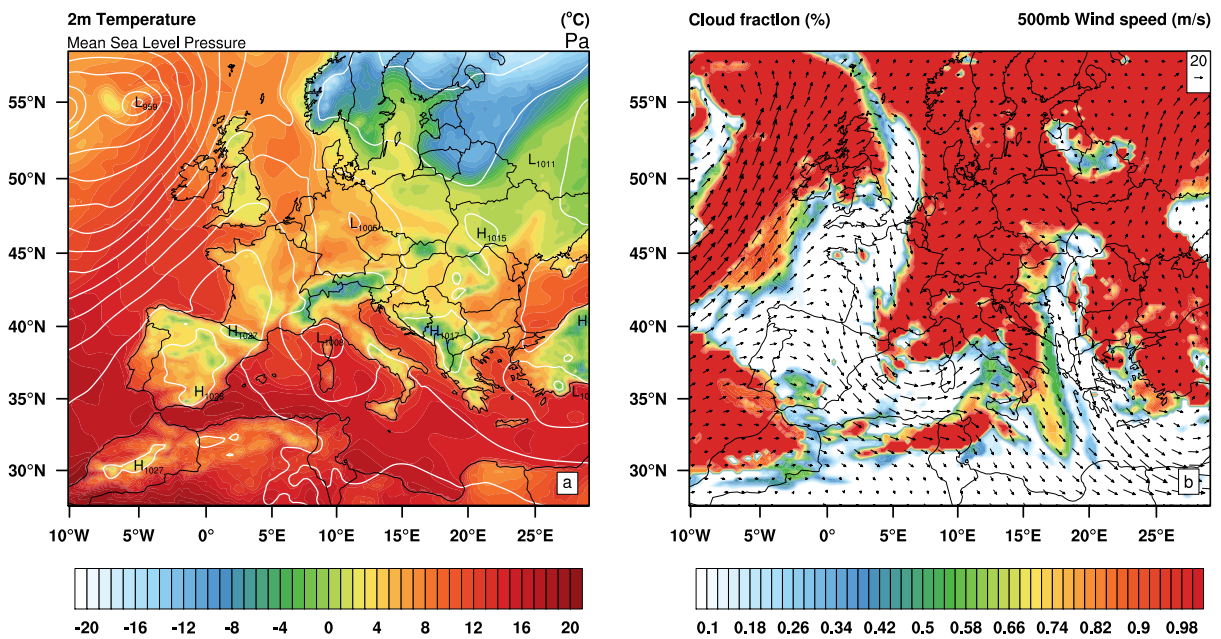


Figure 9. Figure S1: Model synoptic conditions for 15 February 2007 at 00:00hrs, (a) Surface pressure in contours and 2 meter temperature in closed contours, (b) 500 mb wind vector and total cloud area fraction.