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Geoscientific Model Development Discussions

Interactive comment on "Implementation of aerosol-cloud interactions in the regional atmosphere-aerosol model COSMO-MUSCAT and evaluation using satellite data" *by* Dipu Sudhakar et al.

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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 an 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 (1.26e9 and 1.0e8) 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 diustribution 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 ($3.0 \times 10^8 m^{-3}$), 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 $\pm$ 15 and the liquid water exhibits a variation in the range of $\pm$ 0.12 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 aeorosls in COSMO-MUSCAT simulations show an improvement in the cloud microphysical properties. Further, the PDF analsysis has contributed to a quantitative comparison of model reuslts 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 are mean cloud water path in 4i? And how does it compare wit 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 α = 1.37$\times 10^{-5} m^{-0.5}$. 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 Nd 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.

Fig. 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.

Fig. 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.

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Fig. 3. Comparison between COSMO2MR and COSMO2M for 17 February 2007.

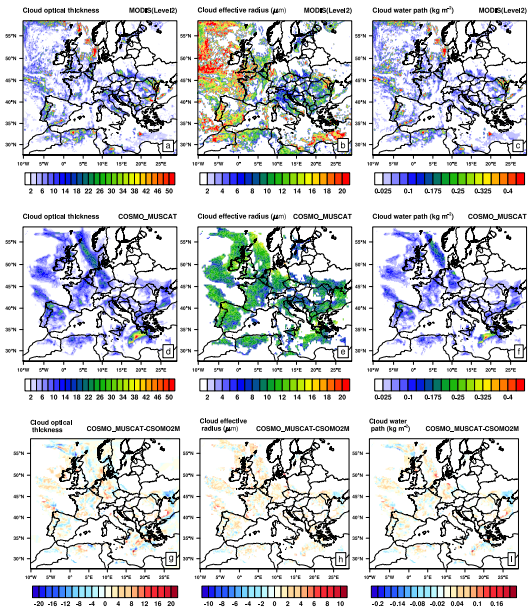

Fig. 4.

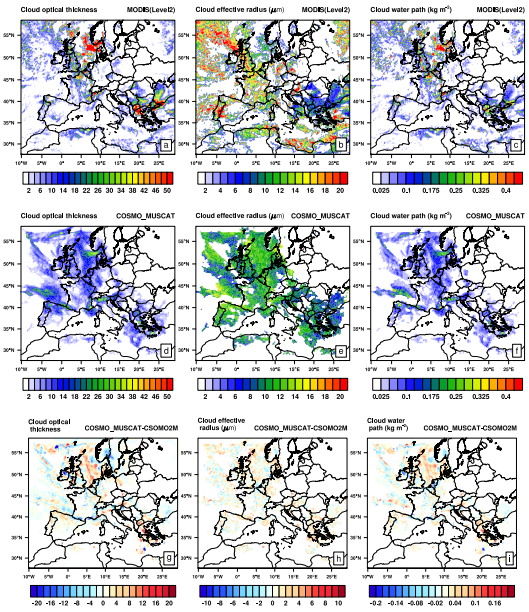
Cloud optical thickness MODIS(Level2)
Cloud effective radius (μm) MODIS(Level2)
Cloud water path (kg m²) MODIS(Level2)
Cloud optical thickness COSMO_MUSCAT
Cloud effective radius (μm) COSMO_MUSCAT
Cloud water path (kg m²) COSMO_MUSCAT
Cloud optical thickness COSMO_MUSCAT-COSMO2M
Cloud effective radius (μm) COSMO_MUSCAT-COSMO2M
Cloud water path (kg m²) COSMO_MUSCAT-COSMO2M

Fig. 5.

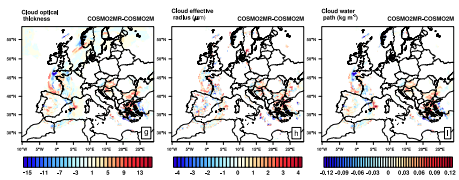
Cloud optical thickness COSMO2MR-COSMO2M
Cloud effective radius (μm) COSMO2MR-COSMO2M
Cloud water path (kg m²) COSMO2MR-COSMO2M

Fig. 6.