Review GMD-2021-188

Title: Evaluation of the COSMO model (v5.1) in polarimetric radar space – Impact of uncertainties in model microphysics, retrievals, and forward operator

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Recommendation: Accept with minor revisions

General comments:

This paper presents an evaluation of the COSMO model for a stratiform precipitation event over Germany. The evaluation is performed using a polarimetric radar network and rain gauges. On the one hand, the evaluation is done using a model-to-observations approach, retrieving synthetic polarimetric signatures from the model with the Bonn Polarimetric Radar Forward Operator. This is complemented by an observations-to-model approach, retrieving synthetic model fields from the observations using several Hydrometeor Classification Algorithms.

The paper discusses a number of fairly simple, but relevant sensitivity tests, including two conversion thresholds within the model microphysics parameterization, and aspect ratio and canting angle assumptions within the forward operator.

Using the model-to-observations approach in combination with an observations-to-model approach, the authors demonstrate nicely which aspects of the evaluation point to real issues with the model assumptions (e.g. overprediction and too slow melting of graupel particles in the default model near and below the melting level, as well as an overprediction of large snow aggregates aloft). Issues with the forward operator are also highlighted as the too large cross-correlation coefficient in all experiments suggest a lack of variability in shapes of the ice hydrometeors.

While the experiments are fairly simple, I think the paper is well-written and structured and presents a very nice example of state-of-the-art techniques in model evaluation with relevant recommendations to the scientific community. Hence, I only have a few minor comments that should probably be addressed before I would recommend acceptance for publication in Geoscientific Model Development.

**We are very thankful for the reviewer's comments. Below, we address the reviewer's specific comments (in bold blue).**

Minor comments:

- L25: Maybe it is worth mentioning the P3 scheme here (Morrison and Milbrandt, 2015), as an example of a microphysics scheme that no longer requires a hard separation in hydrometeor categories.

**Yes, good idea. We added the reference and included the statement**

**Ln 26: "Morrison and Milbrandt (2015) developed an alternative scheme called P3 with only a single frozen hydrometeor class but with explicit prediction of size-dependent hydrometeor bulk densities and fall speeds, based on the prognostic rimed and deposited masses. Such schemes are often tuned in NWP models to …"**

- L115: Since the authors are discussing size distributions here, shouldn't this be the third and zeroth moment, rather than the zeroth and first moments respectively?

**Yes, this formulation was indeed confusing. Zeroth and the first moment are correct, because it is a particle mass distribution (PMD) rather than a PSD. We added a clarifying remark and included the transformation formula from PMD to PSD after Eq. (3).**

- L125: small typo: …, its mu depends on….

**Fixed.**

- L230: Do the authors mean a 340 km by 340 km domain, rathe rather than a domain of 340 km2? If the latter, that would be a very small domain…

**Yes, it is a 340 km x 340 km domain. Fixed.**

- Figure 3: It is worth indicating explicitly in the caption that panel a refers to cloud ice, panel b to snow etc..

**The Figure 3 caption has been updated in the revised manuscript.**

**"QVPs of the model predicted hydrometeor mixing ratios of cloud ice (a,d,g), snow (b,e,h), and graupel (c,f,i) for the CTRL (top row), EXP1 (middle row) and EXP3 (bottom row) runs. Overlaid dashed lines are contours of modeled air temperature QVPs."**

- L312: It is worth referring to Figure 3 here for comparison against the model.

**The reference to Fig. 3 has been added.**

- Table 3: One possibly larger comment is about the microphysics experiment design. How did the authors pick the different values for the snow auto-conversion threshold and the graupel temperature threshold? More specifically, I am not sure I understand the rationale for the differences between EXP2 and EXP3. Wouldn't it be cleaner to only vary the Tgraupel in EXP2 and use values of Dice = 50 µm and Tgraupel = 270.2 K? At the very least, it is not clear to me why the Tgraupel is different between EXP2 and EXP3? Since EXP2 is hardly mentioned, I feel that it might even be worth just removing the experiment from the table and all discussions altogether.

**For the snow auto-conversion threshold, we conducted a sensitivity study using multiple values of Dice (e.g., 5, 50, 150, 400, 800 $\mu m$), the default value being 50 $\mu m$. From these experiments, Dice = 400 $\mu m$ showed the best improvement in the synthetic polarimetric signatures at upper levels, and is used in this study. With Dice=800 $\mu m$, snow-to-ice conversion is limited too much. We chose both the lower and the upper margins of the Dice experimentation range to also check if it has any effect on surface precipitation.**

**We varied Tgr from the default 0°C by reducing it by 5 and 3 °C for EXP2 and EXP3 respectively, to check the sensitivity of graupel production near the melting layer. It showed that the threshold of -3°C was already adequate to reduce the apparently spurious graupel production and that further reduction to -5°C is not necessary. Of course one wants to be as conservative with such thresholds as possible to not affect other, e.g. convection, types of clouds. This also had no effect on the aggregation process above as the change in Dice has negligible effect on this process. Results from EXP2 are discussed in section 4.1.2, with figures in Fig.4 and 9.**

**EXP 1,2,3,4 exhibit different combinations of aggregation (ice/snow partitioning) and riming (graupel production and rain gradient below melting layer), while producing similar domain average precipitation. So, we think all the experiments and discussion therein supports the study.**

**The following paragraph has been added in the revised manuscript to clarify the setup of model sensitivity study:**

**Ln 335: "For the cloud ice aggregation threshold, we conducted a sensitivity study using multiple values of Dice (e.g., 5, 50, 150, 400, 800 $\mu m$), the default value being 50 $\mu m$. For brevity, we only report on the results from one lower and one upper value as well as the default value. From these experiments, Dice = 400 $\mu m$ showed the best improvement in the synthetic polarimetric signatures and is used as the upper Dice value in this study. Similarly, we varied Tgr from the default 0°C by reducing it by 5 and 3 °C respectively, to check the sensitivity**

**of graupel production near the melting layer. The four experiments together constitute different combinations of aggregation (ice/snow partitioning) and riming (graupel production and rain gradient below melting layer).”**

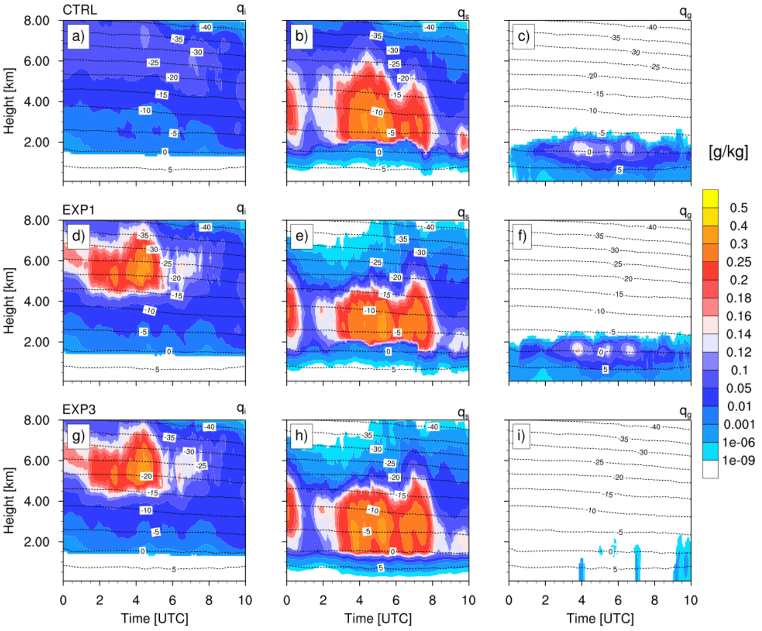
- L340: Not sure I agree that the qr between CTRL and EXP1 are similar. There appear to be much larger peak values of qr in EXP1 than in the CTRL.

**Here, we are suggesting that CTRL and EXP1 do not show the sharp gradient in “qr” as observed for EXP2 and EXP3. However, they do differ in terms of peak values as suggested by the reviewer. The sentence has been rephrased in the revised manuscript:**

**Ln 351: “For example, CTRL and EXP1 do not show the sharp gradient in qr near the melting layer as simulated for EXP2 and EXP3 (Fig. 4). For CTRL and EXP1, qr increases gradually below the melting layer, but differ in peak values. “**

- Figure 4: Could the authors add the panels for EXP1 as well here? That would show more clearly the impact of only the Dice change.

**We assume that Figure 3 instead of 4 is meant here, because in Figure 4 there is already a panel for EXP1. We have now added EXP1 in the revised Figure 3 and the text in Section 4.1.2 has also been modified accordingly.**



- L400: Compare against? Do the authors mean compare Figure 11 against Figure 5?

**Fig.11 (and also Fig.12) includes the median profiles from FO runs with the baseline setup from both the full domain QVP (grey line) and the single-column profiles (thick colored lines), which we intended to suggest being compared. To avoid confusion, we reformulated in the manuscript:**

**Ln 412: “..., the resulting single-column profiles are in general in good agreement with the full-domain QVPs (compare both for the B-PRO$_{def}$ setup in Figs. 11 and 12), ...”**

- L430: Could the authors speculate as to why the ARlow + σlow could lead to a reduction in ρHV? I would think that a low aspect ratio and low canting angle would lead to more uniform behaviour and hence a larger ρHV.

**We thank the reviewer for this particularly interesting question that made us revisit literature and think again and more deeply about our forward operator assumptions and results.**

**Low aspect ratio (note: following Ryzhkov et al. (2011) we define aspect ratio of the oblates as ratio of the semi-minor to semi-major axes), i.e. a higher degree of nonsphericity, generally leads to a decorrelation of the horizontally and vertically polarized signal returns, i.e. to a reduction in $\rho_{HV}$ (e.g. Kumjian, 2013; Melnikov, 2011). This behaviour is observed in our simulations.**

**Higher degree of orientation, i.e. lower widths of the canting angle distribution, is expected to cause a more uniform effective appearance of the scatterers, i.e. higher correlation coefficients. For the cloud ice sensitivity cases of the CTRL run, our results indeed deviate from that expectation, while it is fulfilled in EXP3.**

**Considering that assumption of homogeneous effective-density particles with a deterministic (or even constant) size-shape relation, and oblate spheroids in particular (see e.g. Zrnic, 1994), creates artificial uniformity in the bulk, hence is a notoriously inept assumption, we prefer(red) to not discuss $\rho_{HV}$ further in the manuscript.**

**For the same reason, we did not analyze the origin of that unexpected behaviour further. However, one possible explanation might be the coexistence of several hydrometeor classes, specifically of snow beside the cloud ice. Both classes are individually rather uniform, but create diversity in the bulk when appearing together. Specifically the $AR_{low}$ setup for ice introduces the biggest differences compared to snow, i.e. creates higher diversity in the bulk compared to the other ice sensitivity setups. Also, the canting angle distributions differ the most between the default snow and the $\sigma_{low}$ setups, which might - other than initially expected - create a higher degree of diversity in the bulk.**

**As pointed out before, we did not test this hypothesis. However, it is in line with the absence of this behaviour in the EXP3 case, where no (or very little) snow or other hydrometeor class than cloud ice is present at these heights.**

References:

Morrison, H., J.A Milbrandt, 2015: Parameterization of Cloud Microphysics Based on the Prediction of Bulk Ice Particle Properties. Part I: Scheme Description and Idealized Tests, Journal of the Atmospheric Sciences, 72, 287-311.

**Included.**

**References:**

Kumjian, M. R.: Principles and applications of dual-polarization weather radar. Part I: Description of the polarimetric radar variables, Journal of Operational Meteorology, 1, 226–242, https://doi.org/10.15191/nwajom.2013.0119, 2013.

Melnikov, V.: Polarimetric properties of ice cloud particles, in: 35th Conference on Radar Meteorology, p. 75, American Meteorological Society, ams.confex.com/ams/35Radar/webprogram/Paper191041.html, 2011.

Ryzhkov, A., Pinsky, M., Pokrovsky, A., and Khain, A.: Polarimetric Radar Observation Operator for a Cloud Model with Spectral Microphysics, Journal of Applied Meteorology and Climatology, 50, 873–894, https://doi.org/10.1175/2010JAMC2363.1, 2011.

Zrnic, D. S., Balakrishnan, N., Ryzhkov, A. V., and Durden, S. L.: Use of copolar correlation coefficient for probing precipitation at nearly vertical incidence, IEEE Transactions on Geoscience and Remote Sensing, 32, 740–748, https://doi.org/10.1109/36.298003, 1994.