

This manuscript provides a detailed overview of the development of a new bulk microphysics scheme that includes several classes of ice hydrometeor, as opposed to the typical two classes in older schemes. It also includes the evaluation of a test case in an idealized convective cloud that clearly shows how differences between ice microphysical assumptions impact key properties/processes within a cloud. The further development of ice microphysical schemes is important to better understand how the ice phase influences key cloud properties. However, that message does not come across clearly enough in this work, with the sparse amount of . Similarly, I recommend that the authors undergo more rounds of revision and proofreading before this manuscript is ready for publication. I have included specific comments/questions/suggestions below to aid in the revision.

Response: We expanded the introduction with additional text discussing the benefits, applications and limitations of the new ice mode microphysics scheme. A comparison to other methods that can evaluate ice formation pathways, e.g., tracking of process rates and particle models, was also included.

Introduction

- Here is where I found that the discussion did not cover enough of the work to date to justify the need for a new multi-class scheme, with too little literature cited overall. A couple background topics to consider covering: What is it about two class schemes that make them unsuitable to simulate ice microphysics? What have others done with multi-class schemes and what have they found (consider reviewing the work on the P3 scheme by Morrison and Milbrandt, 2015 and others).

Response: We added a general introduction to bulk microphysic schemes and a list of most commonly used schemes in cloud research (including the P3 scheme). Also we added a comparison of the ice modes scheme to other methods that can be used to investigate ice formation pathways, e.g., super particle models and tracking of microphysical process rates.

Model description

- Lines 142-149: liquid-origin and in situ were already defined in the introduction so I don't think you need to redefine them here

Response: The second definition of the liquid origin and in-situ pathways was removed in the revised manuscript.

- Line 166: why does the saturation adjustment mean that the direct numerical integration of the homogeneous freezing coefficient?

Response: We rephrased the sentence. The parametrization for the nucleation rate for homogeneous freezing of cloud droplets is only valid at water saturation. However, the model is always at water saturation when cloud droplets are present due to saturation adjustment.

- Lines 243-245: the fact that the model does not include an explicit aerosol microphysics model for simulating CCN and INPs, this could be considered for future work

Response: An implementation of the ice modes scheme into ICON-ART, which features an explicit aerosol model, can be considered for future work. However, it is out of scope for this and the following studies. Introducing explicit aerosol microphysics requires the constraint of aerosol sources and sinks. This introduces an additional large uncertainty for model initialization, aerosol transport and emissions.

Climatological aerosol profiles are well constrained and the standard option for cloud microphysics in operational and research model setups. We consider the current implementation of aerosol microphysics sufficient to investigate liquid origin vs in-situ ice formation.

- Figure 2: please readjust panel a such that xtick labels are not overlapping

Response: The issue got correct along side a general stylistic overhaul of figures.

- Section 2.3, consider renaming as the contents cover depositional growth of ice particles so the title may confuse readers

Response: Changed title of subsection into 'Depositional growth of ice particles'.

- Section 2.2.4: consider stating that the differences between these heterogeneous nucleation parameterizations are tested below for an idealized convective case because of the implications on the ice phase in mixed-phase clouds (as stated in the text)

Response: Added an extended introduction for the choices of heterogeneous nucleation schemes and a reference to their comparison in the result section (3.3).

Idealised simulations

- The authors should make it clearer in the text that they tested the new multi-class ice scheme with the three heterogeneous nucleation options by HA, UL, and PH (with the additional PH3) as detailed in Section 2.

Response: We separated the list of experiments from the results section into the (new) method sections (now Section 3.) and added a new introduction to the results section (now Section 4.). This should make the setup of the experiments and the purpose of each of the result sections clearer.

- Please make clearer that the REF scheme refers to the SB scheme with only two ice modes

Response: We expanded the experiments subsection (now Section 3.3) with a clearer explanation of the differences and purposes of the REF and HA experiments.

- It is typical to explicitly state the model version, resolution, and domain (both space and time) up front in a description of experiments, or in the methods section before this. For example, there are several versions of the ICON model, so it should be made clear that the authors ran it in LES mode following Heinze et al. (2017). What other standard configurations are worth noting for your model version? This helps with reproducibility of your results.

Response: With the introduction of the methods section (now Section 3.) the description of the model setup was also expanded (Section 3.1). It contains now more information about the model grid, domain, initial conditions and all physical parametrizations.

- What is the Weisman-Klemp setup? Is it the prescribed temperature and relative humidity profile? Why this set up over others (if available)?

Response: The previous information about the Weisman-Klemp were now moved to a new section in methods (3.2). We also added references to other studies using the Weisman-Klemp setup for the investigation of (idealized) convection and general test of moist atmosphere physics.

- Why is the comparison made only between REF and HA at the start of Section 3.1?

Response: We added a new introduction to the results section (now Section 4.) which explains the purpose of each results section. The first step is to investigate the evolution and structure of the convective cloud for default setup of the ice mode microphysics (now Section 4.1). Then we compare the simulation of the new ice modes scheme (HA) with the reference simulation (REF) in Section (now) 4.2. The only difference in the setup between HA and REF is that HA uses 5 cloud ice classes and REF uses 1 class. The parametrization, especially for the heterogeneous ice nucleation, are the same. Thus we can use the comparison to validate the new microphysics scheme by comparison to the widely used SB scheme. Since REF uses only one ice class, it is reasonable to focus on the comparison of (total) cloud ice (as the sum of all ice modes for HA) and the other hydrometeor classes first (Figure 3.).

For the comparison of the heterogeneous ice nucleation schemes, all experiments were performed with the ice modes scheme. Thus we can focus on the differences in the ice modes.

- In section 3.1 it might be worth noting that you discuss the other panels in figure 3 later on

Response: We added clarification that only two panels are discussed at this point. We did the same for the first mention of Figure 4. in Section 4.1 (previously Section 3.1).

- Line 511, sentence starting with “However, it is heavier...”. Does the “it” refer to ice, as in total ice mass? Maybe consider making this clearer.

Response: The referred lines were expanded and rewritten in the revised manuscript.

- Figures 5, 6, and 7 are generally great. Where did the 0.1 mg/m³ threshold come from?

Response: We added a reference to Wernli et al. (2016) in (new) Section 3.4 for the threshold value. In general, we consider clouds with a mass content of less than 0.1 mg/m³ as too thin to be significant. However, when included, they can distort ice mode mass fraction statistics as explained in Section 3.4.

- Lines 543-544 and Figure 7: “There is significantly more snow present in the ice mode simulation than in the reference simulation.” That does not seem to be the case looking at figure 7. Can the authors explain what they mean more clearly?

Response: We fixed a mislabeling of the Figure 7 panels. In the revised figure, we note that snow in the HA experiment (Panel (a)) is spread over a wider area than in the REF experiment (Panel (b)). The (slight) increase in snow is also noticeable in the temporal evolution of average integrated snow mass content (compare black lines in Figure 3 (a) and (b)).

- Line 547, is this sentence referring to the HA scheme?

Response: We added a clarification. The as ‘HA’ labeled experiment represents the simulation with the ice mode schemes in this section. Both experiments, REF and HA, use the (Hande et al 17., 2015) heterogeneous ice nucleation scheme. The expanded introduction to the experiments in Sections 3.3, 4. and 4.2 should also clarify this.

- Line 588: please state which figure again, and I think the authors might mean panels c and g instead.

Response: We added a reference to the figure here.

Discussion

- Are there any limitations with this new scheme that weren’t addressed by this study that could be considered in future work?

Response: Concerning the liquid origin vs in-situ research question, the ice mode schemes only evaluates from which microphysical formation process the ice crystals stem. It does not track the microphysical history of the ice crystals after their formation. However, the thermodynamic environment that the ice crystals are subject to and grow in (by deposition of vapor) might be as important as their formation process for macrophysical properties of (pure) ice clouds. We will investigate this in the next study.

General

- Several instances of using “an” where there should have been and “a” and vice versa

Response: We made a complete pass through the manuscript to correct this type of mistake specifically.

- Several acronyms weren’t defined before their use or the longname was used after the acronym was defined, check for consistency

Response: We made a pass through the manuscript to ensure that acronyms are always defined before first used. They are also listed in the table of abbreviations in Appendix A. We also corrected instances where the longnames were used in the same sections as the acronyms after their definition. However, for the readability of the manuscript we believe it to be helpful to reintroduce acronyms when they were not used for a several sections. Here we will confer with the editor for stylistic guidelines.

- Are there any observations of precipitation rates that the authors could compare to their new model setup as a test of their new scheme?

Response: We are not aware of a test case based on observations that allows to evaluate the performance of microphysics schemes. As detailed in Section 3.2 the Weisman-Klemp test is widely used as the standard test environment to evaluate microphysics schemes. The validation of the ice modes scheme in this study is done by comparison to the (unmodified) Seifert and Beheng (2006) double-moment scheme, which is widely used in cloud research (Section 4.2). In future studies we will employ the ice mode scheme for studies of real cases. This will include validation by comparison of the ice modes scheme to satellite observations.

References

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