- **RC2**: 'Comment on egusphere-2024-2157', Anonymous Referee #2, 18 Oct 2024

This work introduces new ice classes into an existing cloud microphysics scheme to better elucidate the role of different ice formation mechanisms on the cloud evolution. Since the role of the ice phase on the cloud evolution is still fraught with uncertainty this work and its conclusions are of significance to the scientific community. It is also well written, however some issues must be addressed before publication, as described below.

General comments.

The introduction is almost completely devoid of any citations, despite being full of overarching generalizations. It makes me wonder whether the authors conducted a proper literature review before writing the paper. Please add citations and put the work within the context of the current literature.

It is important to recognize that this is a very idealized model, that although illustrative it might have limited application in the modeling of real situations. The size distribution of the ice crystals is a single function and can't be separated by origin as ice grows. It would be impossible to measure or even estimate the parameters of the distribution for the different ice classes. It is also not recommended to excessively add tracers to be advected by the host model since it may lead to numerical diffusion issues. For host models with lower resolution it would be difficult to relate the different classes to macro-scale variables like cloud fraction and total condensate. Finally, the INP classes used in the work are somehow artificially separated by design while in real cloud they tend to be active at the same time. These considerations must be made clear in the discussion section of the work.

Response: We addressed the concerns of the reviewer in the specific comments. Additional text was added in the 'Introduction' and 'Discussion and Summary' sections to explain the purpose and benefits of the new microphysics scheme and compare it to other methods for investigation of ice formation pathways.

Specific comments

Line 19. Clouds are uncertain in models not in the Earth, please rephrase.

Response: We rephrased the introductory sentences.

Lines 24, 29, 44, 45, 54, 55 and many other places. These statements are not obvious and need references backing them up.

Response: Additional references were added with the rewrite of the introduction.

Line 52. Cloud types.

Response: Fixed misspelling.

Line 59. Remove "will".

Response: Rephrased sentence.

Line 70. Please rewrite this sentence in clearer terms.

Response: An introduction to bulk microphysics schemes in general was added to the introduction.

Line 74. What is f? Should it be normalized to the total mass instead?

Response: Integrating over the size distribution from 0 to infinity we obtain the total number density of particles in the reference volume. Thus, the size distribution is normalized to total number density (or total number concentration if multiplied by air density).

Line 76. Define "the particle mass distribution".

Response: A size distribution describes the number density of particles as a function of the phase space (Hulburt and Katz, 1964). Integrating over the size distribution we obtain the number density (or number concentration if multiplied by the air density) in an interval of the phase space, e.g., in the interval from a particle size of 0 to infinity for the grid box volume. In this model particle size is expressed in terms of its mass. An introduction to (bulk) microphysics schemes in general was added to the introduction.

Line 104. Remove "Actually".

Response: Removed 'actually'.

Line 125. This needs a reference as well.

Response: Added a reference.

Line 135. Remove "huge".

Response: Removed 'huge'.

Line 140. Please clarify what this means.

Response: The section was removed.

Line 154. Should contact ice nucleation be included?

Response: The physics of contact freezing of water droplets is in general not well understood. Including the process in bulk microphysic schemes requires an explicit aerosol model [see, e.g., Hande et al 17. (2017)]. Previous model studies indicate that contact freezing is less effective than other freezing modes (Hande et al 17., 2017).

Line 200. Since competition between homogeneous and heterogeneous nucleation is a significant feature of cloud ice formation, it is not clear how this approach would represent real clouds.

Response: The competition between heterogeneous and homogeneous nucleation is implicitly included in the model. Heterogeneous nucleation (e.g. deposition nucleation) occurs at lower supersaturations (wrt ice) than the homogeneous nucleation threshold. Hence, ice from heterogeneous nucleation can suppress homogeneous nucleation by depleting supersaturation due to depositional growth. If the homogeneous nucleation threshold is still reached, the effect of pre-existing ice (including ice from heterogeneous nucleation) is taken into account as a reduced, fictitious updraft velocity. See Eq. (14) in the manuscript and Kärcher et al. (2006).

Line 210. This expression needs to be weighted by the size distribution of the aqueous solution droplets. In fact, is nhom limited at all by the available droplets?

Response: Kärcher et al. (2002) assume a mono-disperse size distribution for the aqueous solution droplets. The implementation of their homogeneous nucleation parametrization in the ice modes scheme (and also the standard two-moment scheme) also use this simplification. Internally, the number of homogeneously frozen solution droplets within a physical time step is capped by the number concentration of aqueous solution droplets. However, even under ideal conditions only a small fraction of available solution droplets will freeze (Spichtinger and Gierens, 2009).

Line 244. This is a strong assumption that makes this a very idealized model. Please clarify how it might affect the results.

Response: Most bulk microphysics used in operational and research models do not utilize an explicit aerosol model and instead rely on prescribed INP profiles. Introducing an explicit aerosol model requires the initialization and constrainment of aerosol sources and sinks in the model domain, which increases the complexity and uncertainty greatly. Tracking depleted INP as an additional tracer serve to constrain heterogeneous nucleation while not adding the complexity of an explicit aerosol model.

Line 269. This only works for INP immersed within cloud droplets. It is not clear whether it is applied that way.

Response: Since the ice modes (as well as the standard two-moment) scheme do not include an explicit aerosol model, we can not track if an INP is immersed in a liquid droplet or not. As such we consider all INPs activated by the immersion freezing scheme to be immersed in a droplet.

The number concentration of INPs is highly variable and uncertain. Thus we can consider the uncertainty if a INP is immersed in a droplet or not as part of the uncertainty of active INP in general. In a future study we will investigate the sensitivity of the ice mode schemes to the number concentration of profile of INPs.

Line 283. There is an issue here since “na” for deposition and immersion is different (i.e., whether they are inside/outside of cloud droplets).

Response: See response above.

Line 344. Why is this not dependent on the mass of other cloud species?

Response: The number concentration of secondary ice from rime splintering is depended on the rimed mass. Hence the amount of cloud droplet mass converted to graupel and hail. This includes riming of ice, snow, graupel and hail. We added a small section for clarification.

Liner 440. How many new tracers are added to the dynamics scheme? What is the domain of the simulation?

Response: The standard double-moment bulk scheme in ICON (Seifert and Beheng, 2006) uses 14 tracers. The new ice mode schemes uses an additional 8 tracers. Information to the domain and general model setup was expanded in the (new) model setup section (3.1).

Figure 3: Are these lines averaged over the whole domain?

Response: Yes they are the domain averages of the respective Ice Water Paths. We added a clarification in the text and figure labels.

Line 477, 497, 498 and other places. Using words like “weak”, “stronger”, “catches up” is ambiguous. Be precise on the description.

Response: We added quantitative statements to several parts in the results section for more precise descriptions.

Line 477. Not sure what the mass density means here as it has not been used to this point.

Response: Changed all instances of ‘mass density’ to ‘mass content’ for consistency.

Figure 5. Are these zonal means? On what domain?

Response: Figures 5. to 8. show vertical slices of the convective cloud through the center of the domain. Additional information was added in the text and figure captions for clarification.

Line 517. Remove “in an altitude”.

Response: Removed ‘in an altitude’.

Line 531. This separation is by design and may not occur in real clouds.

Response: In real clouds ice particles also originate from a distinct formation process. If we could track individual ice particles from their formation onward in real clouds (or even just in experiments), we would be able to apply the same classification as in this model.

Line 537. Correct “cloude”.

Response: Corrected misspelling.

Line 539. Repeated “are”.

Response: Corrected.

Line 544. Correct the units.

Response: Units were corrected.

Line 551. Please elaborate on this, not sure why there would be an increased number of collisions.

Response: With the addition of new cloud ice classes, the number of collision processes contributing to snow have increased. There are 4 additional calls to ice self collection and 10 new calls to collisions between ice modes. The equations for the ice-ice collision rates are in general non-linear. We added additional information concerning this topic in Section 2.5.2..

Line 557. What bias?

Response: The bias for the ice mode schemes to have higher aggregation rates than the base SB scheme at least in the environment of a deep convection cloud. However, the referred sentence was removed in the revised manuscript.

Line 581. Use “concentration”

Response: Changed all instances of ‘number density’ to ‘number concentration’ for consistency.

Line 589. Correct “then”

Response: Fixed misspelling.

Section 4: please add more discussion on the highly idealized nature of the setup and its implications (see general comment).

Response: We added some text for clarifying this issue in Section 4 (Discussion and summary).

Line 648-650. What is the ground truth here?

Response: The validation of the ice modes scheme in this study is done in Section 4.2 by comparison to the (unmodified) Seifert and Beheng (2006) double-moment scheme (SB06), which is widely used in cloud research. The SB06 scheme uses the same assumptions for the heterogeneous ice nucleation schemes and only differs in the number of cloud ice classes. Both the SB06 and ice modes scheme agree well with regards to evolution of all hydrometeor classes except snow.

References

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