Dear Editor,

We thank the reviewer for thoroughly reviewing our work and providing us with the chance to improve our study. We have carefully considered and incorporated your comments and suggestions into the revised manuscript. We are confident that the alterations made, including those you highlighted, have effectively addressed the concerns.

Please find below the modifications made at the manuscript. The review comments are in black, our point-by-point responses are in red color, and the changes to the manuscript are in blue color.
Sincerely,

Sabine Doktorowski on behalf of all coauthors

Responses to referee comments on the Manuscript "Subgrid-scale variability of cloud ice in the ICON-AES 1.3.00", by Doktorowski et al.

General comments:

This study developed a new scheme for the cloud ice aggregation process, which considers subgrid-scale variability based on a stochastic approach. The authors introduced the scheme into ICON-AES, and evaluated the impact on cloud ice representation against the CloudSat/CALIPSO-based DARDAR product. The new scheme enhances the aggregation rate to reduce cloud ice, which is compensated by decreasing the accretion of ice. Although it was reported that the impact of the new scheme on cloud and radiation fields is not significant, the new approach could provide an important advance in the subgrid-scale representation of ice clouds in future studies.

I feel that the appropriately revised manuscript after the authors include the minor suggestions below may be suitable for publication in Geoscientific Model Development.

Specific comments:

Introduction: There are some previous studies for correcting microphysical process rates by considering subgrid-scale variabilities of hydrometeors, though the approach and target differ from the present study. For example, the analytical formulas for modifying autoconversion and accretion rates in the liquid phase have been developed (Lebsock et al., 2013; Boutle et al., 2014), but I do not know any methods for ice-phase clouds. Adding brief discussions for these previous studies would be helpful for readers and for clearing up the novelty.
Thank you very much for this point, which highlights more the importance and novelty of this study.
Including the subgrid-scale effect in the autoconversion and accretion rate in warm clouds reduces the bias significantly and leads to an enhancement of the process rate (Boutle et al., 2014; Lebsock et al., 2013). Since previous studies mainly focus on warm rain formation processes (e.g., Morrison and Gettelman, 2008; Larson and Griffin, 2013; Boutle et al., 2014; Lebsock et al., 2013), it is also important to concentrate on snow formation effects, by taking subgrid-scale effects into account.

Line 57-58: Could you describe model configurations and parameterizations in more detail? For example, "… for a period from 2005 to 2009 …" may imply nudged configuration, right? Please also add information on the spin-up period and model time-step.
Thank you for the suggestion. We added the informations to the method part: All runs were performed for six years with prescribed sea surface temperature and sea ice boundary conditions for a period from 2004 to 2009 without with instantaneous output every six hours by using a model time step of 10 minutes, a horizontal resolution of 160 km and 47 vertical hybrid sigma levels up to 80 km height (Crueger et al., 2018; Giorgetta et al., 2018). To avoid any effect of the model spin-

up, we ignored the first year from the model results. Therefore all multiyear averages were done for the time period 2005-2009.

Line 57: “with an instantaneously output every . . . ” => “with instantaneous output every . . . ”
We changed the phrase to your suggestion.

Line 60-61: Could you add more specific information about the diagnostic cloud cover scheme?
Thank you for the suggestion. We added to the main text:
The final equation for C, which is used in the model, is given by

$$C = 1 - \sqrt{1 - \frac{r - r_0}{r_{sat} - r_0}}, \tag{1}$$

where r is the relative humidity, r_{sat} is the saturation value (= 1) and r_0 is a function of pressure and depends on two different tuning parameters ($r_{top} = 0.8$ and $r_{surf} = 0.968$), which defines the condensation threshold.

Line 62: How does the model treat precipitating hydrometeors? As far as I know, ECHAM6 physics includes prognostic rain and snow based on Sant et al. (2015), or optional? Please add a brief description of the treatment of precipitation (diagnostic or prognostic) because ice microphysical processes, which is the main focus of this paper, depend strongly on how models treat snowflakes (Michibata et al., 2020). Thank you for this comment. It is indeed very important to add informations on how the model treats snowfall. Therefore we added to the method part: "The ECHAM6 physics includes diagnostic rain and snow profiles in the columns. It is not transported by advection"

Equations (4) and (5): Typo? Please check the symbol “X” in equation (4), and symbols “p0” and “p” in equation (5).
Thank you for checking the equation so carefully. We corrected the symbols in equation (4) (ρ_0 and ρ) and we added "X" in equation (5).

Line 132-134: Consider adding references for CloudSat and CALIPSO missions (e.g., Stephens et al., 2002; Winker et al., 2010).
Winker, D. M. et. al.: The CALIPSO Mission, B. Am. Meteorol. Soc., 91, 1211–1230, https://doi.org/10.1175/2010BAMS3009.1, 2010.
Stephens, G. L. et al.: THE CLOUDSAT MISSION AND THE A-TRAIN, B. Am. Meteorol. Soc., 83, 1771–1790, https://doi.org/10.1175/BAMS-83-12-1771, 2002.
Thank you for the literature suggestion. We added both references to the main text: To evaluate the results, a combined global ice water product of the CloudSat (Stephens et al., 2002) and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Winker et al., 2010), (...)

Line 141-145: I do not have a complaint about the analysis method, but I believe that the comparison between model and observation without separating clouds and precipitating ice is more straightforward. Ice-to-snow conversion is continuous and therefore CALIPSO retrievals cannot separate between cloud ice and snowflake even though using the “precipitation flag”. Noting possible uncertainty would be valuable for readers. And again, how does the model treat snowfall?
Thank you for raising this. It’s indeed an interesting point. The idea of separating cloud ice and snowfall is, that we can compare the cloud ice variance from the model directly with the satellite observations. The cloud ice variance from the model is directly calculated before aggregation started and from the cloud ice, which is available for the aggreagtion. Since the model separates cloud ice and snowfall, we decided it is necessary to use the same method for the satellite data. We agree, that using the precipiation flag in order to remove snowfall from the data set is not completely perfect and therefore, there are still some uncertainties comparing model data and satellite data. We added more text to highlight, that there are still some uncertainties with this methods. Additionally we added, how the model treats snowfall in the model to the method part.

Line 150: “. . . and cloud ice mixing ratio (qi).” => “. . . and cloud ice mixing ratio (qi) obtained from the DARDAR product.”
We added "obtained from the DARDAR product" to the main text.

Line 151: “higher levels” and “lower levels”: This is unclear. Please clearly state by adding pressure levels. Thank you very much for this advise. It was indeed unclear and we changed every "high/low level" cases to a more clear description.

Line 160: The result section starts with “2.4”. Please correct the editorial error in the LaTeX commands. We corrected the error in the LaTex document.

Line 168-169 and Figure 3: Although the model seems to perform well in representing cloud ice distribution, how about column integrated water path (CIWP)? I am slightly concerned about how much the model overestimates CIWP, which directly affects process rates.
Thank you for this point. We included an additional CIWP plot to show the how the model performs in comparison with DARDAR.

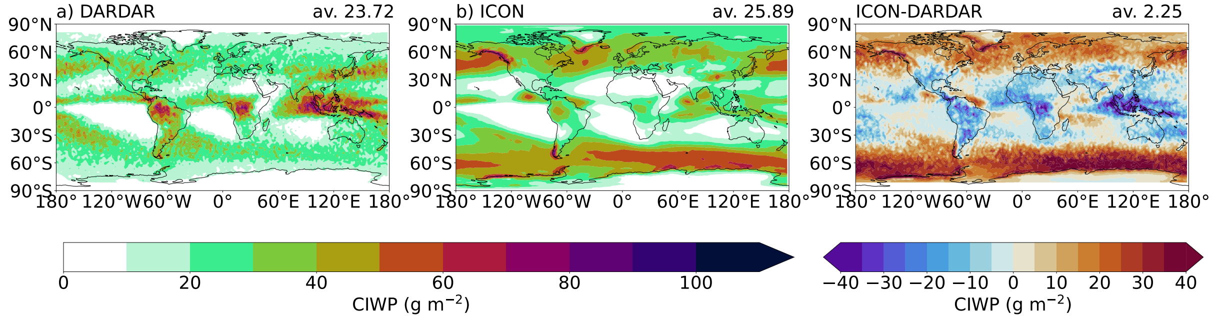

Figure 4. Multiyear cloud ice water path (CIWP) for the DARDAR data and ICON data and the difference between DARDAR and ICON

The cloud ice water path (CIWP), which is the column integrated ice water content, is given in figure 4. ICON overestimates the CIWP in the middle and higher latidues, while it underestimates the CIWP in the tropics. As it was already visible in the figure 3 DARDAR shows larger cloud ice values down the lower altitudes over the tropics, which leads to an increased CIWP compared to the modeled CIWP. Especially in the midlatidues at higher pressure fields the model tend to overestimate the cloud ice. One should keep in mind, that the way the DARDAR data is filtered to get the CIWP or q_i, which is comparable with the model data, is not perfect.

Line 169: Start a new paragraph from “Figure 4 shows . . . ”. We started a new paragraph.

Line 177: Please correct the typo “lebvels”. We corrected the typo.

Line 184: In the caption of Figure 5, the CTRL result was from Tromel et al. (2021). Just to check, were the tuning parameters between CTRL and AGGstoch the same? Please consider adding a note to the main text or figure caption. Thank you for raising this up. We checked all of the tuning parameters and they are the same. We added a note in the main text. "Figure 5 shows its influence on the zonally averaged cloud ice adapted from (Trömel et al., 2021), where the same tuning parameters were use"

Line 201-203: How does the model represent the riming process and Bergeron-Findeisen process? These microphysical processes are also the important source terms for cloud ice and thus snowfall (Gettelman, 2015; Michibata et al., 2020).

Line 206: Insert comma, between “aggregation process rate” and “accretion rate”.
We added a comma to this sentence.

Line 212: Typo “8,9%” => “8.9%” We changed the punctuation.

Line 214 “no important change in radiation is visible (not shown here)”: Consider adding changes in global mean shortwave, longwave, and net radiation at the top-of-the-atmosphere, which would be helpful as a more intuitive metric. Thank you very much for this comment. We included your suggestions with the global mean values in brackets: Due to the small change in the microphysical properties, no important change in global mean shortwave (+0.161 Wm-2), longwave (-0.195 Wm-2) and net-radiation (+0.03 Wm-2) at the top-of-atmosphere is visible (not shown here)

Line 233-234 “Overall we show . . . ”: Start a new paragraph here. We started a new paragraph.

Line 241-242: I feel that a 20% change in the process rate is not significant enough to largely affect radiation and cloud fields. Some studies often show that significant changes in cloud, precipitation, and radiation require modifications of microphysical process rates by a factor of 2 or more (e.g., Imura and Michibata, 2022). In the present study, the authors applied the stochastic method to the aggregation process alone, but it could be extended to other ice microphysics as well (e.g., riming process, accretion among droplets, crystals, and snowflakes) in future studies. When such a framework is incorporated into the model, the impact of the scheme on radiation would be larger than the current model. Please consider adding such brief discussions to the revised manuscript.

Thank you very much for this input. It is indeed a very important point. We added a brief discussion: The effect on radiation was increased, if this stochastic approach could be implemented in other processes, since there has to be a change of a factor 2 or more in microphysical process rates to see an effect on radiation (Michibata et al., 2020; Imura and Michibata, 2022). Using the new approach just for one single process makes it easier in the beginning to see the effect of changing one process, since all processes are connected. Beside from that, the aggregation process is the only non-linear cloud ice process rate in the ICON-AES. Since we focused on cloud ice related processes we just implemented the subgrid-scale approach in the aggregation parameterization. In future studies one can think about including additionally the subgrid-scale approach in the cloud water related processes, in order to see a stronger effect on radiation, cloudiness and precipitation as well.