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Atmospheric Chemistry and Physics Discussions

Interactive comment on "The role of ice nuclei recycling in the maintenance of cloud ice in Arctic mixed-phase stratocumulus" *by* A. Solomon et al.

Anonymous Referee #2

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This manuscript investigates the role of IN recycling from the sub-cloud layer on the persistence of mixed-phase conditions in springtime Arctic stratiform clouds. The study is based on long Large Eddy Simulations of a single mixed-phase stratiform cloud case using prognostic IN concentrations. Several aspects of the problem that deserved more attention from the modeling community are addressed in this work. For example, the role of IN recycling has been isolated here from other potential sources of ice forming particles. In addition, the persistence of mixed-phase clouds has been investigated for rather long periods of time, up to 3 full diurnal cycles (including short-wave solar radiation), when most other LES studies rarely exceed 12-24h. The results and methods presented are thus particularly relevant for the field, and give new insights into the processes maintaining long-lived Arctic mixed-phase stratiform clouds.

I would therefore strongly recommend the publication of this article in ACP. Several issues need however to be addressed in order to improve the overall clarity of the manuscript.

Major comments:

First of all, a more detailed description of the prognostic IN method is required to fully understand the modeling approach and help interpret some of the results. If I understood correctly, there exists two requirements for IN particles within a given bin to activate: 1) the in-situ temperature must exceed the threshold temperature assigned to the bin, and 2) local conditions must be at or exceed water saturation. But how is the nucleation tendency calculated (activation term in equation 1)? I guess that the number of particles within bin k is initially given by the number of IN calculated by equation 2 at the threshold temperature $k + 1$ minus that calculated at temperature k. But are all the particles (or 50% of them) within bin k activated instantaneously as soon as the threshold temperature k is exceeded (at or above water saturation)? In other words, is ice nucleation considered to be an instantaneous process or is it allowed to vary smoothly in time? This may be of importance as IN recycling involves interactions between sublimation, droplet activation and freezing, with droplet activation often considered to occur instantaneously, and ice nucleation being a much slower, and thus limiting, mechanism. Also, is the F factor used in equation 2 applied at each time-step, i.e. is the number of activated IN after each time-step equal to 50% of the unactivated particles within the bin at the beginning of the time-step? Finally, can you please comment on the relevance of omitting the dependence of IN nucleation on water and ice saturation? In particular, assuming that IN particles are available for nucleation as soon as water saturation is reached suggests that the particles acting as IN, whatever they are, activate as cloud droplets at water saturation, regardless of their size and composition. Should we expect different conclusions on the role of IN recycling if

activation and freezing were assumed to be size and composition dependent (and thus more sensitive to water saturation)?

The results section is very concise, with very clear figures, and gives the essential information needed to understand the outcome of the study. The analysis of IN and NI fluxes through cloud base provides interesting insights on the mechanisms involved in the maintenance of IN concentrations sufficient to sustain mixed-phase cloud conditions. However, several points deserve clarifications. First of all, Figure 6 shows that ice production and IN activation are larger around cloud base. This result seems to contradict former modeling studies showing that ice formation primarily occurs at cloud top, where the temperature is lower. A short discussion of the vertical distribution of IN activation, which peaks at cloud base, may provide interesting information. A key aspect of the study resides in the IN reservoir formed by the sub-cloud mixed layer. While SubCL NIN decreases much faster than CL NNI after 10h, it seems that NIN also increases faster than NNI before 10h in the control run (there is a jump of $\sim$200 mL-1 for NIN compared to $\sim$100 mL-1 for NNI). This looks almost like more IN particles are released in the sub cloud layer than ice crystals are formed in the cloud. Could you please clarify this point and explain why sub-cloud NIN increases so rapidly at first? How do the total number NIN+NNI in the cloud and sub-cloud layers evolves in each case (this could be an addition to figure 7d)? Also, what is causing the reversal in the integrated NIN trend after 10h while sublimation fluxes remain roughly constant?

Looking at Figures 7 & 8, it seems that the simulated clouds in the control and noRecycle runs are almost identical at the beginning of the analysis period, that is at 6h. Only the IN flux through cloud base is initially different between the two cases, highlighting the influence of sub cloud IN recycling. Could you indicate why is recycling apparently so unimportant in controlling the cloud properties before 6h? Moreover, on p11738-l14/17, it is stated that "the rapid increase in LWP [...] increases the

turbulent mixing of IN from the sub cloud layer into the cloud layer". This statement seems however to contradict Figure 8b where the IN turbulent fluxes at cloud base are always lower in noRecycle compared to control. Finally, Figure 8b also shows almost constant sublimation fluxes in the control run during the whole simulation time. Sublimation should however release water vapor and thus reduce the sublimation rates and IN recycling. This does not appear to be the case here. How can sublimation be sustained at nearly constant rates in these conditions, without the sub-cloud layer becoming saturated with respect to ice? How do ice saturation and the water vapor mixing ratio evolve in the sub-cloud layer in your simulations? Additional figures showing the evolution of ice saturation, water vapor mixing ratio and temperature in the sub-cloud layer might help. More generally, relative humidity in the mixed-layer seems to be the most important ingredient determining the role of IN recycling in sustained ice production. From that perspective, how representative is the studied case compared to typical AMPS?

Minor comments and technical corrections:

- p11728-l24: "a liquid layer that precipitates ice crystals" sounds a bit strange. Please consider rephrasing.
- p11729-l20: "mineral dust, soot, sea salts and bacteria", as well as the list of references given l22-24. Perhaps match the corresponding references with the different IN compounds, i.e. "mineral dust (Mohler et al., 2006; Welti et al., 2009...), soot (DeMott, 1990...), sea salts (Wise et al., 2012)...".
- p11730-l22/26: "We posit that recycling plays a significant role more generally since, for example, assuming an adiabatic vertical profile, a 650 m-deep mixed layer with a cloud-top temperature of -16C requires a water vapor mixing ratio of at least 1.7 gkg-1 at mixed-layer base to be saturated with respect to ice, i.e,

in order for recycling to be a negligible source of ice nuclei in the mixed layer." The sentence may be slightly too long. Please consider splitting or rewording it. Besides, isn't it a little bit too strong to suppose that IN recycling may be significant unless the mixed-layer is saturated with respect to ice (if I understood correctly the meaning of this sentence)?

- p11731-l24/26: "a cloud layer extending into the inversion by 100 m, cloud base at 0.9 km, and cloud top at 1.5 km." How stable were these conditions? How did the cloud boundaries evolve in time according to the radar retrievals? How long did the AMPS persist over Barrow?

- p11732-l10: How was the average value of 0.4 L-1 calculated based on the 2D-S and 2D-P probes? Is it an average from the two devices, or were data from 2D-S and 2D-P for different size ranges combined?

- p11732-l24: How was this particular value of the divergence (2.5ex10-6 s-1) selected? What about the initial surface pressure and surface fluxes?

- p11734-l12/23: I would suggest moving the paragraph at the end of the section, i.e. after the description of the IN/recycling parameterization.

- p11736-l6/7: If I am correct, 5.8 L-1 is the TOTAL IN concentration, i.e. the sum of the NIN in each bin. Maybe this should be specified. Also, it could be interesting to have an idea of the NIN distribution with respect to the threshold temperature. You could for example indicate what the IN concentration within the first and last bins is. Besides, is there any particular treatment required for the first bin as it includes all the particles active between -15.5C and 0C? Is it correct and realistic to say that all the IN within the first bin spontaneously nucleate ice as soon as water saturation is reached, i.e. at cloud base?

- p11736-l23: Is it a liquid or a mixed-phase cloud layer?

- p11737-l2 (and whole text): Notations "N_{NI}" (number of ice crystals) and "N_{IN}" (number of IN) can be easily confused. Perhaps a different notation for the number of ice crystals could be used.

- p11740-Equation 7 and p11741-Equation 8b: Perhaps change the notation and add a subscript to f to distinguish between cloud base and mixed-layer base values. Also describe more clearly what allows you to transform equation 8b into 8c.

- p11741-l18: "In SW": please rephrase to introduce more clearly the sentence (maybe "in the presence of short wave radiation", is it what you mean?).

- p11741: The analysis does not account for any water vapor flux. Sublimation releases water vapor in the sub-cloud layer, and vapor is also transported through the mixed-layer boundaries by turbulence. With the water vapor content possibly increasing in the sub-cloud layer, we may expect the sublimation flux to decrease. How would this be reflected in the simple mixed-layer model, and what would happen in case of a saturated mixed-layer with respect to ice?

- p11741-end of page: Please provide a short summary of the main implications for actual AMPS clouds, and for the conditions under which IN recycling is relevant.

- p11742-l3: If I understand correctly, the start of the green arrow corresponds to sunrise, the tip of the blue arrow corresponds to maximum SW, and the tip of the red arrow corresponds to sunset. Am I right? It looks actually like the moon and sun symbols on Figure 11761 are not absent in the manuscript.

- p11742-l5/7: What causes the relative humidity to be low at this time? More generally, what causes the simulated RH cycle despite continuous sublimation and surface decoupling? Besides, what happens to the precipitation flux at this time?

- p11742-l23/24: An increase in in-cloud ice concentrations could enhance the precipitation fluxes in the sub-cloud layer and may dominate over the decrease in downward turbulent NI flux. Why isn't it the case here? More generally, the role of precipitation should be more specifically stressed in section 6. To complement the discussion, it may also be interesting to compare the states at the beginning and at the end of a full diurnal cycle (Figure 11 shows only a 20h cycle).
- p11743-l2: Sub-cloud drying has not been mentioned earlier in the study, and Figure 11 does not seem to confirm that. A figure showing the evolution of below cloud humidity in the control and SW runs would be very instructive. Again referring to my main comment, relative humidity in the mixed-layer is a key ingredient controlling IN recycling via sublimation. Can you please comment on this and stress the relevance of the case study presented compared to typical AMPS.
- Figure 1: The grey shadings do not appear clearly or are absent.
- Figure 3: Could you please add a legend and axis labels to the figure?
- Figure 4: In the caption, I guess that the second sentence refers to figure c).
- Figure 7, 8 & 10: The horizontal axis labels and titles are missing.