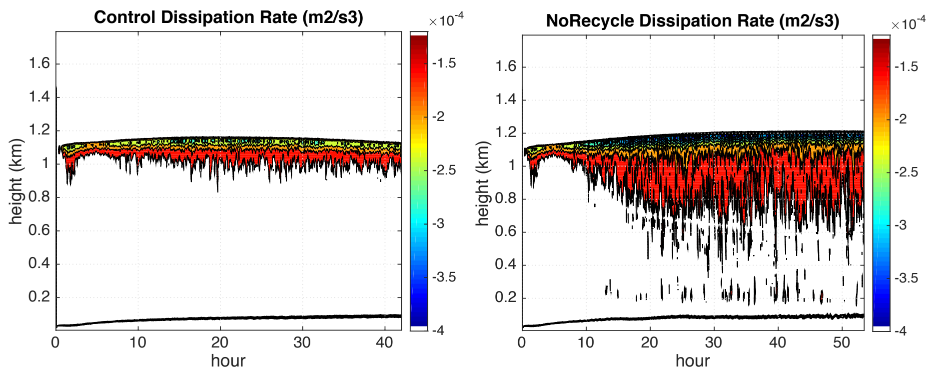
We thank both reviewers for their thoughtful and constructive comments. Revising the paper to address their concerns has significantly improved the manuscript. We have addressed the concerns expressed in the reviews as completely as possible in the point-by-point responses and in the revised paper. The reviewers' comments are in black font and our responses are below each comment in blue font.

Reviewer #1

1 General Comments

This study investigates the persistence and liquid-ice phase partitioning of mixed-phase stratocumulus clouds typical of the Arctic. The authors suggest that subcloud ice crystal sublimation produces ice nuclei that recycle back into the cloud layer to reactivate ice particles. The recycling of ice nuclei act to maintain the ice water content over a longer time-scale than without recycling, and with the combination of cloud-top radiative cooling, both liquid and ice contents can be steadily maintained. The authors also imply a diurnal impact on the maintenance of mixed-phase stratocumulus in that both liquid and ice productions are weakened in the presence of shortwave radiation, which in turn reduces ice precipitation fluxes out of the layer, and hence further prolonging the lifetime of the system.
Previous studies on the maintenance of mixed-phase stratocumuli involve the discussion of the rapid glaciation and dissipation of these clouds due to efficient ice depositional growth via the evaporation of the liquid content, usually at higher ice concentrations. Because ice nuclei recycling effectively maintains a consistent ice concentration, it would be curious to see what role recycling would play in liquid/cloud dissipation rates.

The dissipation rates are proportional to the TKE in each run. Here are figures of the dissipation rates for Control and NoRecycle:



Maximum TKE in NoRecycle is ~28% larger than Control because of the larger LWP which is consistent with the ~32% increase in the maximum dissipation rate.

Furthermore, figures 7a and 10a indicate that, over time, the liquid water content achieves higher values when the diurnal cycle is consistent, in contrast to the ice water content, which drops to lower values. This result is not discussed, but one would imagine that the diurnal cycle would also help to maintain a mixed-phase cloud that would otherwise dissipate.

On page 11742 line 9 we have added, "…and promotes the persistence of a mixed-phase cloud system.".

The work presented is very interesting and compelling. The recycling technique appears to compare well with previous work that employ relaxation ice concentration methods for simpler studies, and so perhaps the recycling effect could be considered a motivation for simulations with assumed constant ice concentrations. The manuscript is well written, concise, and organized thoughtfully. The manuscript content and figures, however, are very compact and complex, so I would urge the authors to consider simplifying and/or shortening sentences throughout for ease of reading. I would also encourage the authors to simplify figures so that they are easier to interpret.

Thank you, we have gone through the manuscript to identify sentences that can be simplified and shortened.

With the advice given above and the suggestions listed below, my recommendation for this manuscript is *accept for publication with major revisions*.

2 Specific Comments

1. Page 11729, Lines 4-7, "However, unlike subtropical...at cloud top": Which process are considered to dissipate subtropical mixed-phase clouds that do not occur in the Arctic? One would imagine that subtropical clouds could also be supplied with moist air at cloud top. Are AMPS unique from all other mixed-phase stratocumuli in other regions (e.g., midlatitudes)? If so, is there a specific quality (e.g., temperature, solar zenith) in AMPS to contribute to these differences?

   This sentence has been changed to read, "However, unlike subtropical cloud-topped boundary layers where decoupling enhances cloud breakup by cutting the cloud system off from the surface source of moisture, decoupled AMPS can persist for extended periods of time due to weak precipitation fluxes out of the mixed layer and relatively moist air entrained into the cloud layer at cloud top.

2. Page 11730, Line 22, "We posit that recycling...": The term "recycling" has been used many times thus far, but has never been defined or conceptually explained.

   A clarifying sentence has been added on page 11730 at line 12, "This feedback loop is referred to hereon as "recycling".

3. Page 11730, Line 27, "...while AMPS...": Perhaps change to "...while persistent AMPS". AMPS are not necessarily always persistent, so please be sure to differentiate throughout.

   Sentence changed as suggested.

4. Page 11731, Line 2: Please indicate whether recycling is turned off or on for the Control simulation as it is never indicated.

Lines 3-4 have been changed to, "…with recycling turned on and shortwave radiation turned off (to compare with previous simulations of this case that use different IN formulations and shortwave radiation turned off)…"

5. Page 11735, Line 2: Are the IN that are produced via sublimation always recycled back into the layer? Is it possible that some IN become "inactive" after sublimation?

Yes, recycling just means IN become available for activation but the extent to which they become active depends on large-scale circulation, mixing by turbulent eddies, and the in-situ temperature and water vapor. The sentence has been left unchanged.

6. Page 11735, Lines 8-13: Interpretation of figure 2 is unclear. Do you only consider activation at these threshold temperatures, or would a concentration of 1.3-1.5/L nucleate at -20versus 0.75/L at 15oC? What is unique about these temperatures that make them "threshold"?

"used to initialize IN number concentration in each bin" has been added to the Figure 2 caption. After initialization prognostic equations for each bin that include advection, turbulent mixing, and sources and sinks are used to calculate the evolution of IN in each bin. The threshold temperatures are a representation of the dependence of nucleation on surface characteristics and size. The nucleation scheme used in this study approximates this relationship with the number of IN available as a function of a threshold temperature (given the discrete bins used in this study) based on the empirical study of DeMott et al. (2010). Threshold temperatures are only needed because we are discretizing the continuous relationship shown in Figure (2).

7. Page 11735, Line 22: What is the importance of the "modification of activation thresholds" and why is this consideration unnecessary for this work?

The sensitivity of ice nucleation to the preactivation of IN is an interesting topic but outside the scope of this study since it is so poorly defined by measurements at this time. This will be included in future studies if laboratory studies can quantify the impact of preactivation on ice nucleation.

8. Page 11736, Lines 13-14: "Crystal size...Fig. 5": Why would the maximum ice size (5 mm) be larger than the maximum snow size (0.7 mm) in Figure 5? What are the shape or aspect ratios and densities considered for snow and ice? What are the physical processes considered for snow and ice?

"ICE" and "SNOW" need to be reversed in the legend in Figure 5. This has been corrected. In our model setup, the particles are assumed to be spherical and d is set equal to 3. The bulk density of ice is assumed to be 0.5 g cm^{-3} and the bulk density of snow is assumed to be 0.1 g cm^{-3}. Beside the nucleation parameterization described in the paper, ice and snow mass can change due to riming, condensation/deposition, and autoconversion.

9. Page 11736, Line 24: To interpret figure 6, it would help to mention that IN are "lost" to activation of ice crystals.

The sentence has been changed to read, "IN are produced by sublimation of ice crystals below the cloud layer, advected to the cloud layer by turbulence, and removed from the population when activated as ice crystals"

10. Page 11737, Lines 15-23, "Over the...subcloud layer": If the cloud was coupled, could you expect different results since rather than the turbulent eddies sweeping the IN back into the cloud, the IN could sediment to lower levels and not be recycled.

Yes, if the cloud becomes coupled to the surface layer then eddies can mix IN in layers from the surface to the cloud base into the cloud layer and the IN reservoir at the base of the mixed layer is quickly activated. This causes more IN to be lost from the system through increased precipitation.

11. Page 11737, Lines 23-25, "The continuous...mixed-layer base." This statement is unclear. Is this statement suggesting a "residence time" effect in that IN are advected into the cloud layer out of the subcloud layer more quickly than new IN produced via crystal sublimation?

Yes, this is correct. There is a continual depletion of IN from below the cloud layer while the ice number concentration decreases more slowly. This is seen clearly in Figures 8b and 10e where sublimation is less then the IN flux at cloud base. The sentence has been left unchanged.

12. Figure 7b: Perhaps this is already explained, but why does the temperature warm more for recycling? Perhaps recycling induces activation which increase the release of latent heat? This should be discussed.

The temperature is colder for the NoRecycling case because there is more liquid in the cloud and therefore stronger cloud top cooling, which is mixed downward by cloud-driven turbulent mixing. Differences in latent heat release are not as significant as differences in radiative cooling at cloud top (not shown). A sentence has been added on page 11738 line 13, "Increased cloud liquid water when recycling is turned off results in increased radiative cooling at cloud top, which causes the cloud-driven mixed layer to cool more rapidly (Figure 7b)."

13. Figure 7d: Please explain the units m L (meters/liter?).

In Figure 7 caption "(meters/liter)" added.

14. Figure 10c (number in column): The feedback loop in figure 9 is not apparent in figure 10c as one would expect oscillations in N_{NI} to correspond with those in N_{IN}.

This would only be the case if precipitation, turbulent mixing and entrainment are negligible, which is not the case for this simulation. The schematic has been left unchanged.

3 Technical Corrections

15. Page 11729, Line 10: "radiatively-important" should be "radiatively important".

Changed as suggested.

16. Page 11729, Line 26: Please replace the semi-colon (;) with either a colon (:) or a comma (,).

Changed as suggested.

17. Page 11729, Line 28: Please remove the first "or".

Changed as suggested.

18. Page 11730, Line 11: Both "large-eddy" and "large eddy" have been used.

"large-eddy" has been replaced with "large eddy".

19. Page 11730, Line 13: While it may be obvious to most readers, please consider expanding D.O.E.

Changed as suggested.

20. Page 11733, Line 7: "horizontal resolution" should be "horizontal resolutions"

Changed as suggested.

21. Page 11733, Line 23: Please replace "amplitude" with "amplitudes".

Changed as suggested.

22. Page 11733, Line 28: Please replace "...where the slope of liquid-ice static energy exceeds..." with "...where the slopes of liquid-ice static energy exceed..."

Changed as suggested.

23. Page 11734, Line 28: Water vapor mixing ratio has already been defined.

Second definition removed.

24. Page 11739, Line 13: "Figure" should be "Figures".

Changed as suggested.

25. Page 11741, Line 8: "control" to indicate the control case is sometimes capitalized and other times not.

"Control" is used uniformly throughout the paper.

26. Page 11742, Please consider absorbing the first paragraph into the second as the first paragraph contains only one sentence.

Changed as suggested.

27. Figure 1: There is an overlap in the x-axes of the two plots. Also, the caption indicates "grey shading" that does not appear in the figure.

The figure has been corrected.

28. Figure 3: Please add a legend.

A legend has been added.

29. Figure 4: This caption is very difficult to follow. Perhaps consider removing the first three sentences as that information is contained in the image. Also, please add the "control" lines to Figs. 4B and D and legends to B-D.

Thank you for your comment but we would like to keep the first three lines in the caption to identify the fields plotted in each figure. The wording of the caption has been simplified to clearly specify the fields plotted in each panel. Control LWP and IWP have been added to 4B and 4D. Legends are now in all four panels.

30. Figure 6 and throughout: Please consider relabeling the number of ice crystals to something like N_i as N_{IN} and N_{NI} are very easily confused.

"N_{NI}" and "T_{NI}" have been changed to "N_{ICE}" and "T_{ICE}" to clearly distinguish from "N_{IN}" and "T_{IN}".

31. Figures 7a and b: Are IWP and temperature calculated for just within the cloud, within the mixed layer, or for the entire domain.

IWP and minimum temperature are calculated for the entire column. The caption has been changed to read, "Minimum horizontally-averaged temperature in the column, in units of ^oC."

32. Figures 7, 8, and 10 are missing plot labels as referenced in the captions (e.g., a, b, c, d) and x-axes.

Labels and axes added.

33. Figure 10: “CB”, “CL”, and “ML” should be defined in the caption. Also, what do the grey shaded columns indicate?

All abbreviations and shading are now defined in the figure caption.

Reviewer #2

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.

Yes, this is correct. IN number concentrations are initially specified using equation 2, such that the initial IN in bin *k* is equal to the number of IN calculated by equation 2 at the threshold temperature *k + 1* minus that calculated at temperature *k.* After the initial time 50% of the IN available in a bin nucleates if the in-situ temperature is above the threshold temperature and the local conditions exceed water saturation. This approach is motivated by the study of Ervens and Feingold (2013; doi:10.1002/grl.50580), where it was shown that, for Classical Nucleation Theory, nucleation rates are far more sensitive to temperature (T) than to time. If we consider the same nucleation rate, an uncertainty of ΔT = +/- 0.2 K translates to the same uncertainty as differences in time of about two orders of magnitude.

Regarding observations of time dependent nucleation as in Westbrook and Illingworth: Ervens and Feingold (2013) note that "Based on our analysis, we estimate that differences of five orders of magnitude in t (10s vs. 1day) are equivalent to a change of ΔT ~–2K (at T ~258K, i.e., the approximate T of the observed clouds)." This happens to be the same T as our Arctic case. So observations that suggest a time dependence might actually be masking small(ish) T fluctuations that are hard to measure at high spatial temporal resolution. However, temporal aspects of nucleation may play an interesting secondary role and is currently an active area of research. These temporal aspects need to be investigated in a Lagrangian model since in an Eulerian model temporal information is not available. Therefore, within the model framework of an Eulerian bin model we can represent IN distributions as a function of temperature but not time.

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?

Yes, this is correct. As discussed above, the factor F is applied at every time step such that 50% of the unactivated IN nucleate if the in-situ environment is saturated with respect to water and the in-situ temperature is above the threshold temperature for that bin.

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)?

Yes, we are only including ice nucleation where drops are a necessary precondition. We are actually including the dependence of IN nucleation on water and ice saturation by using an empirical relationship between IN and temperature to specify the initial IN number concentrations in each bin. The number of IN available for nucleation in each bin is an implicit function of temperature, composition, and size. This is the simplest parameterization for IN that doesn't include aspects of nucleation that the model cannot resolve.

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 figure has been added of the time evolution of the horizontally-averaged ice+snow number concentration and IN advection+subsidence (shown below in Figure S1). This figure shows that the majority of IN activates at cloud base, which is a bit warmer than cloud top but is sufficiently cold to activate many of the IN. However, IN from bins with colder threshold temperatures are advected higher into the cloud where they activate at their threshold temperature. A secondary maximum is seen at cloud top where the coldest temperatures are found. Also, it is seen that IN are advected into the cloud layer at cloud top for the first 15-18 hours, but this source of IN decreases as IN in the upper entrainment zone are depleted.

Regarding how this fits with other model studies, the location of particle nucleation is based on how IN processes are specified in each model. If nucleation is simply diagnosed based on temperature, then it will occur more towards cloud top. The use of a prognostic equation to describe IN evolution in this study causes there to be a source of IN below the mixed-phase cloud layer that can nucleate ice given the right conditions near cloud base. Observationalist, such as Alexei Korolev, have suggested from measurements that all sizes of frozen hydrometeors are observed near cloud top (suggesting turbulent mixing of hydrometeors within the cloud layer). In addition, it is very difficult to distinguish this information from remote sensors because there is a mixture of new small particles combined with the larger particles that are growing and eventually fall faster than the updrafts. This is consistent with the results from our model studies, where ice activates quickly and then is efficiently mixed with snow in the mixed-phase cloud layer. This is clearly seen in Figure S1a, where ice+snow number concentrations are well-mixed in the cloud layer. Results from these model studies, remote sensing of mixed-phase clouds, and in-situ measurements highlight the difficulty of determining where ice nucleates in a cloud layer that is well-mixed by turbulent eddies. This discussion has been added to Section 4.1.

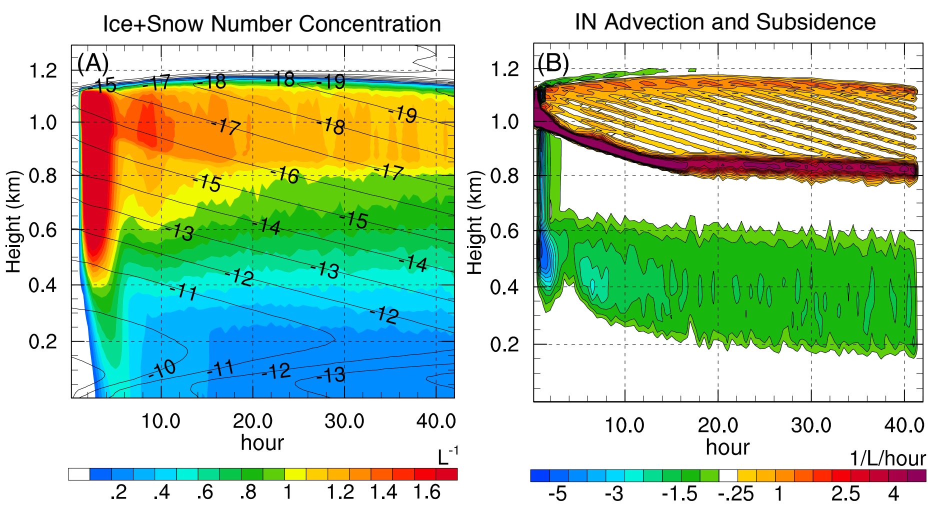


Figure S1: Time-height cross sections of (A) ice+snow number concentration, in units of L^{-1}, and (B) IN advection plus subsidence, in units of $L^{-1}hour^{-1}$, from CNT simulation. Temperature, in units of °C, shown with black contour lines.

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 ~200 mL-1 for NIN compared to ~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?

The rapid increase in subcloud N_{IN} is due to the rapid deepening of the mixed-layer (due to the height of the mixed-layer base) in the first 10 hours, seen Figure 8c. After the first 10 hours the mixed-layer deepens at a slower rate.

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?

This is because the NoRecycle run is started with the Control state at hour 6 in order to prevent the runs from diverging during spinup. A sentence has been added on page 11734 line 20 which reads, ‘The NoRecycle run is started from the Control run at hour 6 to prevent the two simulations from diverging due to spinup.”. Apologies for leaving this information out of the first version of the paper.

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.

Turbulence is larger in NoRecycle due to the larger LWP but the IN gradients are smaller due to the rapid depletion of IN, therefore the turbulent flux of IN at cloud base is smaller in NoRecycle compared to Control. The sentence has been left unchanged.

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?

Two time-height cross sections of horizontally-averaged relative humidity with respect to ice and water vapor mixing ratio have been added to the paper in Figure 7c,d. The Figure shows the continuous drying of the sub-cloud layer due to the dominance of the drying due to the water vapor flux over the moistening due to sublimation. This is what allows sublimation to be maintained in the simulations. The consistent drying and cooling of the mixed layer due to radiative cooling and turbulent mixing in these simulations is fundamental in any AMPS that is precipitating ice out of the mixed layer and has limited fluxes of water vapor at the mixed layer base. Of course, if water vapor fluxes at the mixed-layer base increases to the extent that the mixed layer becomes saturated with respect to ice then recycling will be shut off.

Minor comments and technical corrections:

1. p11728-l24: "a liquid layer that precipitates ice crystals" sounds a bit strange. Please consider rephrasing.

   The sentence has been rewritten to read, "AMPS are characterized by a liquid cloud layer with ice crystals that precipitate from cloud base even at temperatures well below freezing…".

2. 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)...".

   Sentence changed as suggested.

3. 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)?

   Yes, this sentence is worded too strongly. We feel the sentence read better as one sentence and does not need to be split into two sentences. The wording has been rewritten to read, "We posit that recycling may make IN available for nucleation more generally since,…".

4. 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?

This sentence has been changed to read, “Measurements from ground-based, vertically pointing, 35-GHz cloud radar, micropulse lidar, and dual-channel microwave radiometer at Barrow indicated a mixed-phase cloud layer starting at 8UTC on 8 April 2008 with a cloud top at approximately 1.5km that slowly descended to approximately 0.5 km over a 26 hour period. At the time of the 17:34 sounding the cloud layer extended into the inversion by 100 m, had a cloud base at 0.9 km, and cloud top at 1.15 km.”

5. 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?

The data from the 2D-S and 2D-P were averaged to together to get an average number concentration. The sentence has been reworded to read, “Ice crystal number concentrations measured by Stratton Park Engineering Company 2D-S and Particle Measuring Systems 2D-P optical array probes for sizes larger than 100 mm together averaged 0.4 L^{-1}.”

6. 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?

The section on the divergence has been changed to read, “Divergence is assumed to be $2.5x10^{-6}s^{-1}$ below the temperature inversion and zero above, giving a linear increase in large-scale subsidence from zero at the surface to $2.7mms^{-1}$ at the base of the initial inversion (z = 1.1 km). This value for divergence was chosen so that the height of the temperature inversion at cloud top is steady. The divergence used in this study is smaller than the divergence used in the WRFLES study of the same case by Solomon et al. (2014) due to the reduced LWPs in this current study and therefore reduced turbulent entrainment that balances large-scale subsidence in a steady simulation.” In addition, the sentence, “Initial surface pressure is 1020 hpa.” has been added before the description of divergence.

Additional details have been added about the surface layer scheme, “Surface fluxes are calculated uses the modified MM5 similarity scheme with calculates surface exchange coefficients for heat, moisture, and momentum following Webb (1970) and uses Monin-Obukhov with Carlson-Boland viscous sub-layer and standard similarity functions following Paulson (1970) and Dyer and Hicks (1970).”

7. 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.

The paragraph has been moved to after the description of the IN/recycling parameterization.

8. 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?

Page 11736 lines 4-5 have been changed to read, "…an initial N_{IN} summed over all bins at every gridpoint equal to 5.8 L^{-1}…" Also, at line 6 a discussion has been added regarding initial N_{IN} in each bin, " In a discrete bin formulation this results in 3.26 L^{-1} in the warmest bin and 0.23 L^{-1} additional IN that are available for nucleation in the coldest bin. Given the initial temperatures in the cloud layer, all IN from the first bin in the cloud layer nucleate. This causes an initial spike in cloud ice number concentration, which also causes a large precipitation flux out of the mixed layer. It takes approximately 6 hours for the cloud layer to reach a quasi-equilibrium with steady cloud ice production. "

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

"liquid" has been changed to "mixed-phase".

10. 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.

Yes, this is confusing. "N_{NI}" and "T_{NI}" have been changed to "N_{ICE}" and "T_{ICE}" to clearly distinguish from "N_{IN}" and "T_{IN}".

11. 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.

Thank you but we think the notation for f is clear and does not need a subscript. To clarify the steps that allow for the transform between eqs. 8b and 8c, "…and since $f|_{\text{Mixed-Layer Base}}$ is downward and $f|_{\text{Mixed-Layer Top}}$ is negligible (eq. 5), …" has been added between eqs. 8b and 8c.

12. 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?).

The sentence has been changed to read, "In the presence of shortwave radiation (i.e., in the SW simulation),…".

13. 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?

A saturated mixed-layer with no sublimation does not change the mixed-layer analysis presented in Section 5. However, from eq 8c using the same assumptions of $f|_{\text{Mixed-Layer Base}}$ is downward and $f|_{\text{Mixed-Layer Top}}$ is negligible, when S=0,

$$T_{IN}|_{\text{Mixed-Layer Base}} < T_{IN}|_{\text{Cloud Base}}$$

causing IN to be depleted in the mixed layer since entrainment at cloud top is weak.

Also, see the two time-height cross sections of horizontally-averaged relative humidity with respect to ice and water vapor mixing ratio that have been added to the paper in Figure 7c,d. The Figure shows the continuous drying of the sub-cloud layer due to the dominance of the drying due to the water vapor flux over the moistening due to sublimation.

14. 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.

This discussion has been added at the end of page 11741, “This mixed-layer analysis provides a framework to understand the results presented in Section 4. Specifically, sublimation being less than the turbulent flux of IN is seen to be a property of a well-mixed layer where the total flux at mixed-layer base is downward and the total flux at the mixed layer top is negligible. In the case where the mixed layer is saturated with respect to ice, sublimation is equal to zero and the turbulent flux of IN at the mixed-layer base is less that the turbulent flux of IN at the cloud base, reducing the flux of IN into the cloud layer. The relationships outlined in this section are appropriate for any AMPS with weak entrainment at cloud top, weak large-scale advective fluxes, and net downward fluxes at the mixed-layer base.”.

15. 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.

The start of the green arrow corresponds to maximum SW (see Figure 11b). The arrows are used as a means to refer to transitions in the cloud mixed-layer properties. Again, apologies for the missing symbols. It must have been a challenge to review this paper with incomplete figures and we appreciate the effort that you have gone to to understand the results of this study.

16. 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?

When incoming solar radiation is at a maximum, LWP is at a minimum, which causes turbulent mixing to be at a minimum. Also, the cloud layer and mixed layer warm, causing less ice production and less precipitation into the subcloud layer. The warming of the subcloud layer together with the reduction in precipitation causes the relative humidity to be at a minimum.

17. 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).

We actually do say here that both IWP and precipitation increase when incoming solar radiation is a minimum. There is a net downward flux of NI out of the cloud layer. This discussion was just meant to point out that turbulence acts against this downward flux. Figure 11 shows a 24-hour cycle, the red arrow only extends to hour 62 and the green arrow begins at hour 42, while the cycle is for the 40-64 hour period.

18. 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.

Two time-height cross sections of horizontally-averaged relative humidity with respect to ice and water vapor mixing ratio have been added to the paper in Figure 7c,d. The Figure shows the continuous drying of the sub-cloud layer due to the dominance of the drying due to the water vapor flux over the moistening due to sublimation. Fig. 7 also shows the time-height cross sections of horizontally-averaged water vapor mixing ratio and relative humidity with respect to ice. This brief discussion has been added at the end of the second paragraph in Section 4, "Fig. 7 also shows the time-height cross sections of horizontally-averaged water vapor mixing ratio and relative humidity with respect to ice. These figures show that the continuous drying and cooling of the mixed layer results in continuous sublimation in the subcloud layer."

19. Figure 1: The grey shadings do not appear clearly or are absent.

There seems to have been a problem with the figures in the online version of the paper. I'm sorry I didn't catch this before the paper was sent out for review. All the figures are complete in the revised paper.

20. Figure 3: Could you please add a legend and axis labels to the figure?

I'm sorry, I don't know why the legends and labels were removed from the online version of the paper. We will make sure the revised version is correct.

21. Figure 4: In the caption, I guess that the second sentence refers to figure c).

The figure caption has been reworded for clarity, "A,B,D) Sensitivity of LWP and IWP to snow density and fall speeds. LWP shown with solid lines and IWP shown with dashed lines, in units of g m^{-2}. C) Fall speeds used in sensitivity studies, in units of m s^{-1}….".

22. Figure 7, 8 & 10: The horizontal axis labels and titles are missing.

Our apologies for this. The labels and titles were removed in the online version for some reason. We have added the labels and titles back in and will insure that the revised online version is complete.

The Role of Ice Nuclei Recycling in the Maintenance of Cloud Ice in Arctic Mixed-Phase Stratocumulus

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Abstract

This study investigates the maintenance of cloud ice production in Arctic mixed phase stratocumulus in large eddy simulations that include a prognostic ice nuclei (IN) formulation and a diurnal cycle. Balances derived from a mixed-layer model and phase analyses are used to provide insight into buffering mechanisms that maintain ice in these cloud systems. We find that for the case under investigation, IN recycling through subcloud sublimation considerably prolongs ice production over a multi-day integration. This effective source of IN to the cloud dominates over mixing sources from above or below the cloud-driven mixed layer. Competing feedbacks between dynamical mixing and recycling are found to slow the rate of ice lost from the mixed layer when a diurnal cycle is simulated. The results of this study have important implications for maintaining phase partitioning of cloud ice and liquid that determine the radiative forcing of Arctic mixed-phase clouds.

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1 Introduction

Reliable climate projections require realistic simulations of Arctic cloud feedbacks. Of particular importance is accurately simulating Arctic mixed-phase stratocumuli (AMPS), which are ubiquitous and play an important role in regional climate due to their impact on the surface energy budget and atmospheric boundary layer structure through cloud-driven turbulence, radiative forcing, and precipitation (Curry et al., 1992; Walsh and Chapman, 1998; Intrieri et al., 2002; Shupe and Intrieri, 2004; Sedlar et al., 2011; Persson, 2012). For example, Bennartz et al. (2012) showed that the extreme melt events observed at Summit, Greenland in July 2012 would not have occurred without the surface radiative forcing produced by AMPS.

AMPS are characterized by a liquid cloud layer with ice crystals that precipitate from cloud base even at temperatures well below freezing (Hobbs and Rangno, 1998; Intrieri et al., 2002; McFarquhar et al., 2007). Radiative cooling near cloud top generates turbulence that maintains the liquid layer and forms an approximately well-mixed layer that extends as far as 500 meters below cloud base. These cloud-driven mixed layers are frequently decoupled from the surface layer, limiting the impact of fluxes of heat, moisture, and aerosols on the cloud layer from below (Solomon et al., 2011; Shupe et al., 2013). However, unlike subtropical cloud-topped boundary layers where decoupling enhances cloud breakup by cutting the cloud system off from the surface source of moisture, decoupled AMPS can persist for extended periods of time due to weak precipitation fluxes out of the mixed layer and relatively moist air entrained into the cloud layer at cloud top (Tjernström et al., 2004; Solomon et al., 2011; Sedlar et al., 2012; Solomon et al., 2014).

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AMPS are challenging to model due to uncertainties in ice microphysical processes that determine phase partitioning between ice and radiatively important cloud liquid water (Sandvik et al., 2007; Tjernström et al., 2008; Klein et al., 2009, Karlsson and Svensson, 2011; Barton et al., 2012; Birch et al., 2012; de Boer et al., 2012), which drives turbulence that maintains the system. Phase partitioning depends upon the number, shape, and size of ice crystals, since these determine the efficiency of water vapor uptake by ice and hence the availability of water vapor for droplet formation (Chen and Lamb, 1994; Sheridan et al., 2009; Ervens et al., 2011; Hoose and Möhler, 2012).

Since temperatures in AMPS are too warm for homogenous ice nucleation, ice must form through heterogeneous nucleation. Aerosols with properties to serve as seeds for heterogeneous ice crystal formation are referred to as ice nuclei (IN). A number of different aerosols such as mineral dust (Broadley et al., 2012; Kulkarni et al., 2012; Lüönd et al., 2010; Möhler et al. 2006; Pinti et al., 2012; Welti et al., 2009), soot (DeMott, 1990), sea salts (Wise et al., 2012), and bacteria (Kanji et al., 2011; Levin and Yankofsky, 1983) have been observed to act as IN, all of which nucleate at different temperatures and supersaturation ranges. In addition, observations indicate that nucleation properties are modified by aging and coating of aerosols (Möhler et al., 2005; Cziczo et al. 2009). Heterogeneous ice nucleation can occur by a number of modes: either in the presence of super-cooled droplets, when an aerosol comes into contact with a droplet (contact freezing), is immersed in a droplet (immersion freezing), or by vapor deposition on IN (deposition freezing) (Pruppacher and Klett, 1997).

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IN can be entrained into the cloud-driven mixed layer through turbulent mixing from above and/or below. Recent studies indicate that entrainment alone cannot account for observed ice crystal number concentration (N_{ICE}) (Fridlind et al., 2012), motivating the use of diagnostic formulations for ice formation to produce model simulations of AMPS with realistic phase partitioning (Ovchinnikov et al., 2011). While this modeling strategy constrains N_{ICE} to be close to the measured values it eliminates the dynamical-microphysical feedbacks that regulate ice/liquid phase partitioning (Avramov et al., 2011).

Here we investigate a relatively unexplored source of ice production--recycling of ice nuclei in regions of ice subsaturation. AMPS frequently have ice-subsaturated air near the cloud-driven mixed-layer base where falling ice crystals can sublimate, leaving behind IN. This feedback loop is referred to hereon as "recycling". Recycling was found to be significant in large eddy simulations of a single-layer stratocumulus observed during the Department of Energy Atmospheric Radiation Measurement Program's Mixed-Phase Arctic Cloud Experiment (M-PACE; Verlinde et al., 2007; Fan et al., 2009). AMPS observed during M-PACE formed due to a cold-air outbreak, where large fluxes of heat and moisture over the open ocean forced turbulent roll clouds that were coupled to the surface layer. This coupling with the surface layer prevented the identification of the role of dynamics internal to the cloud-driven mixed layer in maintaining phase-partitioning.

In this study we focus on the internal microphysics and dynamics of the cloud-driven mixed layer by investigating processes in an AMPS decoupled from surface sources of moisture, heat, and ice nuclei. We posit that recycling plays a significant role more generally since, for example, assuming an adiabatic vertical profile, a 650 meter-deep mixed layer with a cloud-

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top temperature of -16°C requires a water vapor mixing ratio of at least 1.7 g kg^{-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. This value is typically only seen in the Arctic between May-September (Serreze et al., 2012), while persistent AMPS frequently occur outside of these months (Shupe et al., 2011).

We examine the role of IN recycling in maintaining ice production using large eddy simulations of a springtime decoupled AMPS. Three simulations are analyzed; a "Control" with recycling turned on and shortwave radiation turned off (to compare with previous simulations of this case that use different IN formulations and shortwave radiation turned off), "NoRecycle" with IN recycling turned off to identify the impact of recycling on the cloud life-time and phase partitioning, and "SW" with recycling and shortwave radiation turned on to identify the impact of realistic diurnal heating and cooling tendencies on the recycling process. This study builds on previous studies of this case, all of which exclude shortwave radiation (Avramov et al., 2011; Solomon et al., 2011, 2014), by including a prognostic equation for IN and a diurnal cycle. Within this modeling framework we investigate the relative roles of recycling and entrainment of IN in maintaining cloud ice production.

2 Case Description

The case derives from observations of a persistent single-layer Arctic mixed-phase stratocumulus cloud observed near Barrow, AK on 8 April 2008 during the Indirect and Semi-Direct Aerosol Campaign (McFarquhar et al., 2011) (see Fig. 1). The adjacent Beaufort Sea was generally ice covered during this time, with significant areas of open water observed east of Barrow. A 4-K temperature inversion with inversion base at 1.05 km was observed

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via a radiosonde at 17:34UTC; static stability was near neutral within the mixed layer overlaying a stable near-surface layer with static stability greater than 2 K km^{-1} below 500 m. The water vapor mixing ratio, q_v, decreased from 1.7 g kg^{-1} at the surface to 1.2 g kg^{-1} at cloud top, above which a secondary maximum of 1.6 g kg^{-1} was observed. Winds were east-southeasterly throughout the lowest 2 km.

Measurements from ground-based, vertically pointing, 35-GHz cloud radar, micropulse lidar, and dual-channel microwave radiometer at Barrow indicated a mixed-phase cloud layer starting at 8 UTC on 8 April 2008 with a cloud top at approximately 1.5km that slowly descended to approximately 0.5 km over a 26 hour period. At the time of the 17:34 sounding the cloud layer extended into the inversion by 100 m, had a cloud base at 0.9 km, and cloud top at 1.15 km. Cloud ice water path (IWP), derived from cloud radar reflectivity measurements, varied from 20–120 g m^{-2} within 10 min of the sounding, with an uncertainty of up to a factor of 2 (Shupe et al., 2006). Concurrently liquid water path (LWP), derived from dual-channel microwave radiometer measurements, was 39–62 g m^{-2}, with an uncertainty of 20–30 g m^{-2} (Turner et al., 2007).

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Research flights were conducted by the National Research Council of Canada Convair-580 at 22:27-23:00 UTC on 8 April 2008 over the ocean northwest of Barrow (McFarquhar et al., 2011). Droplet concentrations measured by a Particle Measuring Systems Forward Scattering Spectrometer Probe varied between 100 and 200 cm^{-3}. Ice crystal number concentrations measured by Stratton Park Engineering Company 2D-S and Particle Measuring Systems 2D-P optical array probes for sizes larger than 100 μm together averaged 0.4 L^{-1}. IN concentrations measured with the Texas A&M Continuous Flow Diffusion Chamber varied from 0.1 L^{-1} to above 20 L^{-1}. Ice crystal habit estimated using the automated habit classification procedure of Korolev and Sussman (2000) indicated primarily dendritic crystal habits.

3 Model Description

We use the large eddy simulation mode of the Advanced Research WRF model (WRFLES) Version 3.3.1 (Yamaguchi and Feingold, 2012) with the National Center for Atmospheric Research Community Atmospheric Model longwave radiation package (Collins et al., 2004), RRTMG shortwave package (Iacono et al., 2008), the Morrison two-moment microphysical scheme (Morrison et al., 2009), and a 1.5-order turbulent kinetic energy prediction scheme (Skamarock et al., 2008). Surface fluxes are calculated uses the modified MM5 similarity scheme with calculates surface exchange coefficients for heat, moisture, and momentum following Webb (1970) and uses Monin-Obukhov with Carlson-Boland viscous sub-layer and standard similarity functions following Paulson (1970) and Dyer and Hicks (1970).

All model runs are initialized with winds, temperature, and water vapor from the 17Z 8 April 2008 sounding at Barrow, AK (see Fig. 1). Initial surface pressure is 1020 hPa. Divergence is assumed to be $2.5\text{x}10^{-6}$ s^{-1} below the temperature inversion and zero above, giving a linear increase in large-scale subsidence from zero at the surface to 2.7 mm s^{-1} at the base of the initial inversion (z=1.1 km). This value for divergence was chosen so that the height of the temperature inversion at cloud top is steady. The divergence used in this study is smaller than the divergence used in the WRFLES study of the same case by Solomon et al. (2014) due to

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the reduced LWPs in this current study and therefore reduced turbulent entrainment that balances large-scale subsidence in a steady simulation.

All simulations are run on a domain of 3.2 × 3.2 × 1.8 km with a horizontal grid spacing of 50 m and vertical spacing of 10 m. The domain has 65(x)×65(y)×180(z) gridpoints and is periodic in both the x- and y-directions. The top of the domain is at 1.8 km, which is 0.7 km above cloud top in this case. The model time step is 0.75 s. The structure of the cloud layer is insensitive to changes in resolution and domain size. For example, tests run for Solomon et al. (2014) demonstrated that increasing the vertical and horizontal resolutions by a factor of two resulted in an increase in LWP and IWP by 5% and 1%, respectively, while increasing the domain size by a factor of two in both the x- and y-directions results in an increase in LWP and IWP of less than 1%.

Cloud droplets are activated using resolved and subgrid vertical motion (Morrison and Pinto 2005) and a log-normal aerosol size distribution (assumed to be ammonium bisulfate and 30% insoluble by volume) to derive cloud condensation nuclei spectra following Abdul-Razzak and Ghan (2000). The aerosol accumulation mode is specified with concentrations of 165 cm^{-3}, modal diameter of 0.2 μm, and geometric standard deviation of 1.4 μm, based on in situ ISDAC measurements. In this formulation, IN and cloud condensation nuclei are treated as separate species.

Temperature and moisture profiles are nudged to the initial profiles in the top 400 m of the domain with a time scale of 1 hour. The model is initialized with winds, temperature, and water vapor similar to the Control integration from Solomon et al. (2014). Horizontal winds are nudged to the initial profiles at and above the initial inversion base with a timescale of 2 hours. Initial temperature and subgrid turbulent kinetic energy (TKE) are perturbed below the top of the mixed layer with pseudo-random fluctuations with amplitudes of +/- 0.1 K and 0.1 $m^2 s^{-2}$, respectively. The liquid layer is allowed to form in the absence of ice during the first hour of the integration to prevent potential glaciation during spinup.

The cloud-driven mixed layer is defined as the region where the liquid-ice water static energy is approximately constant with height. We define the boundaries of the mixed-layer top and base to occur where the slopes of liquid-ice static energy exceed 7x10^{-3} K m^{-1} and 1x10^{-3} K m^{-1}, respectively. Cloud top and base are defined as the heights where cloud water mixing ratio, q_c, is equal to 1x10^{-4} g kg^{-1}.

Nested Weather Research and Forecasting (WRF) model simulations of this case performed with an inner grid at LES resolution (Solomon et al. 2011) demonstrate that moisture is provided to the cloud system by a total water inversion at cloud top and that the mixed layer does not extend to the surface, i.e., the mixed layer is largely decoupled from surface sources of moisture. In addition, the nested simulations indicate that cloud liquid water, q_c, is maintained within the temperature inversion by downgradient turbulent fluxes of q_v from above and direct condensation driven by radiative cooling. These processes cause at least 20% of q_c to extend into the temperature inversion.

WRFLES has been modified to include a prognostic equation for IN number concentration (N_{IN}),

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$$\frac{\partial N_{IN}}{\partial t} + ADV + DIFF = \left.\frac{\delta N_{IN}}{\delta t}\right|_{activation} + \left.\frac{\delta N_{IN}}{\delta t}\right|_{sublimation} \qquad (1)$$

where ADV represents advection and DIFF represents turbulent diffusion. Activation is also referred to as nucleation of ice and sublimation is also referred to as recycling of IN.

Here we adopt an empirical approach by initializing N_{IN} with an observationally based relationship expressing the number of available IN as a function of temperature in regions of water-saturation (DeMott et al., 2010),

$$N_{IN} = \mathrm{F} * 0.117 \exp\left(-0.125 * (\mathrm{T} - 273.2)\right) \qquad (2)$$

where F is an empirically derived scale factor and T is temperature in Kelvin. Sixteen prognostic equations are integrated for N_{IN} in equally spaced temperature intervals with nucleation thresholds between -20.2°C and -15.5°C (see Fig. 2). Therefore, additional IN become available for activation as the cloud layer cools. Initial N_{IN} concentrations are a function of the nucleation threshold temperatures and are independent of the in-situ temperature. The in-situ temperature in regions of water saturation determines how many IN are activated. To take deviations from the empirical derivation into account, IN are activated with 50% efficiency (by multiplying the activation tendency in equation (1) by 0.5), however results are insensitive to this parameter (not shown). Due to the pristine dendritic nature of the observed crystals, ice shattering and aggregation are neglected in the simulations and sublimation returns one N_{IN} per crystal.

N_{IN} (in units of L^{-1}) integrated over the domain in each temperature bin k at time t is equal to

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$$\overline{N}_{IN}(k,t) = \iiint N_{IN}(x,y,z,k,t)\ dx\, dy\, dz. \qquad (3)$$

Upon sublimation, the modification of activation thresholds that can occur for previously nucleated IN, i.e. preactivation (Roberts and Hallett, 1967), is not considered and N_{IN} are returned to each bin k with weighting

$$\mathrm{W}_k = [\overline{N}_{IN}(k,0) - \overline{N}_{IN}(k,t)\,]/\ \overline{N}_{IN}(k,0) \qquad (4)$$

where W_k is normalized such that $\sum \mathrm{W}_k = 1$. The W_k are recalculated each time step. In this way, IN are recycled preferentially to each of the 16 temperature bins from which they originated (Feingold et al., 1996).

The factor F in Eq. (2) is set to 4 for all simulations yielding an initial N_{IN} summed over all bins at every gridpoint equal to 5.8 L^{-1}, compared to 10 L^{-1} used in LES studies of the same case presented in Avramov et al. (2011). In a discrete bin formulation this results in 3.26 L^{-1} in the warmest bin and 0.23 L^{-1} additional IN that are available for nucleation in the coldest bin. Given the initial temperatures in the cloud layer, all IN from the first bin in the cloud layer nucleate. This causes an initial spike in cloud ice number concentration, which also causes a large precipitation flux out of the mixed layer. It takes approximately 6 hours for the cloud layer to reach a quasi-equilibrium with steady cloud ice production. Supplementary integrations were done to test for robustness of the results presented in Section 4 by varying initial IN concentrations, i.e., the factor F, (shown in Fig. 3) and by varying snow density and fall speeds (shown in Fig. 4). Fig. 3 shows that the simulation maintains ice production when the initial N_{IN} is increased or decreased by ~3 L^{-1} relative to Control. Fig. 4 shows that the

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simulations maintain quasi-steady ice and liquid water paths after an initial spinup but the amount of ice produced is sensitive to the snow fall speed.

Crystal size distributions for averaged values of ice water mixing ratio and number concentration from the Control integration are shown in Fig. 5. These crystal size distributions are consistent with the Avramov et al. (2011) simulations of this case where crystal habits are assumed to be high-density pristine dendrites. The distribution shown in Fig. 5 underestimates the number of large (greater than 5mm) crystals as estimated by the 2D-S and 2D-P probes (see Avramov et al. (2011) for a detailed discussion of the measurements).

The Control integration is run with shortwave radiation turned off in order to compare with previous LES studies of this case (Avramov et al. 2011; Solomon et al. 2014). The results of Control are compared to two additional simulations; one with IN recycling turned off (hereafter "NoRecycle") and one with recycling and shortwave radiation both turned on (hereafter "SW"). SW is used to investigate how the diurnal cycle impacts IN recycling and ice formation. All runs use the same setup except SW has subsidence reduced by 30% to keep the mixed-layer top from lowering appreciably because of smaller LWPs. This allows for direct comparisons of mixed layer structure and fluxes at the mixed layer boundaries. The NoRecycle run is started from the Control run at hour 6 to prevent the two simulations from diverging due to spinup. The first six hours of integration are not used in the analysis to allow for the spinup of cloud ice. Hours 6-40 are used for analysis of the Control and NoRecycle simulations and hours 16-76 are used for analysis of the SW simulation to allow for multiple diurnal cycles.

4 Model Results

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4.1 Control Integration

In the quasi-steady Control integration, the mixed-layer depth is approximately 850 m and comprises a 375 m deep mixed-phase cloud layer (henceforth "the cloud layer"), extending above the mixed-layer top by 25 m, and a 500 m subcloud layer below (Fig. 6). IN are produced by sublimation of ice crystals below the cloud layer, advected to the cloud layer by turbulence, and activated as ice crystals (Fig. 6). Ice that forms in the cloud layer is transported vertically by turbulence, precipitates to cloud base and below, and sublimates below the cloud layer. At the mixed-layer base, an increase in N_{ICE} due to precipitation approximately balances a decrease in N_{ICE} due to sublimation. These processes constitute a feedback through which ice production and IN recycling are closely related. This feedback between ice production and IN in the mixed layer is linked to dynamic-thermodynamic tendencies, which sustain a subsaturated subcloud layer because the decrease in relative humidity due to an upward turbulent vapor flux exceeds the increase due to sublimation.

The time evolution of horizontally-averaged IN advection plus subsidence (Fig. 7a) shows that the majority of IN activate at cloud base, which is a bit warmer than cloud top but is sufficiently cold to activate many of the IN. However, IN from bins with colder threshold temperatures are advected higher into the cloud where they activate at their threshold temperature. A secondary maximum is seen at cloud top where the coldest temperatures are found. Also, it is seen that IN are advected into the cloud layer at cloud top for the first 15-18 hours, but this source of IN decreases as IN in the upper entrainment zone are depleted. The turbulent mixing of snow and ice in the mixed-phase cloud layer is clearly seen in Fig. 7b, where ice plus snow number concentrations are well-mixed in the cloud layer. Given the

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efficient mixing by the turbulent eddies, it is not possible to identify whether ice has nucleated at cloud base or cloud top from the ice number concentrations alone. Fig. 7 also shows the time-height cross sections of horizontally-averaged water vapor mixing ratio and relative humidity with respect to ice. These figures show that the continuous drying and cooling of the mixed layer results in continuous sublimation in the subcloud layer.

LWP and IWP remain steady until hour 16 of the simulation, and decrease slowly thereafter (solid lines in Fig. 8a). LWP and IWP magnitudes are within the observational estimates for this case. In addition, the cloud system is sustained over a multi-day period similar to measurements taken during ISDAC. Continuous cloud-top cooling causes the minimum horizontally-averaged temperature (near cloud top) to decrease from -17.5°C to -20°C from hour 10 to hour 40 (Fig. 8b).

Over the 40-hour integration, the cloud layer remains decoupled from the surface (Fig. 8c). However, this does not prevent the number concentration of ice crystals (N_{ICE}) in the cloud layer from remaining relatively steady, decreasing from vertically integrated values of 372 to 365 m L^{-1} (Fig. 8d, or in terms of vertically averaged cloud layer values, 1.2 L^{-1} to 1.1 L^{-1}). By contrast, while N_{ICE} is maintained in the cloud layer, N_{IN} in the subcloud layer decreases significantly from 2 L^{-1} to 0.2 L^{-1} over the same period. Therefore, even though more N_{ICE} are lost from the cloud than are activated (Fig. 9a), the relatively constant flux of IN into the cloud layer (Fig. 9b) allows N_{ICE} in the cloud to decrease at a slower rate than N_{IN} in the subcloud layer. The continuous loss of N_{IN} in the subcloud layer is due to the IN flux into the cloud layer exceeding the N_{IN} gained through sublimation and turbulent advection at mixed-

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layer base (Fig. 9b). This loss is not mitigated by entrainment at mixed-layer top, which is found to be negligible (Fig. 9c), consistent with Fridlind et al. (2011).

The feedback loops discussed above are illustrated by the conceptual diagram in Fig. 10, where any change to one link in the cycle leads to an increase or decrease in ice production. For example, a decrease in the turbulent advection of N_{IN} into the cloud layer, slows the activation of IN, reduces the precipitation flux into the subcloud layer, reducing sublimation and availability of IN below cloud base. Both dynamics and thermodynamics play a role in the buffering aspect of these feedback loops since, for example, the slowing of IN activation in the example above would lead to increased cloud liquid production, cloud-top radiative cooling, and enhanced turbulent mixing, which would lead to increased transport of IN into the cloud layer and therefore increased activation of IN.

4.2 Impact of turning off recycling

When IN recycling is turned off, all IN that activate are lost from the system. This results in a more rapid loss of IN, a decrease in IWP, and a rapid increase in LWP (Fig. 8a,d, dashed lines), in contrast to the measurements that show a steady liquid layer and consistent ice production. Increased cloud liquid water when recycling is turned off results in increased radiative cooling at cloud top, which causes the cloud-driven mixed layer to cool more rapidly (Fig. 8b). These results demonstrate the importance of IN recycling in regulating phase partitioning. The rapid increase in LWP increases cloud-generated turbulence via enhanced radiative cooling and increases the turbulent mixing of IN from the subcloud layer into the cloud layer, contributing to a more rapid depletion of IN relative to the Control integration. This process eventually becomes limited due to depletion of IN in the reservoir

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below (Fig. 9b). Due to the additional activation of IN as the cloud layer cools, ice production is maintained in the absence of recycling and the activation of IN in the cloud layer exceeds the upward IN flux at cloud base (Fig. 9a,b). However, the diminishing N_{IN} in the subcloud layer limits IN activation and N_{ICE} rapidly decreases in the cloud layer (Fig. 8d).

4.3 Impact of diurnal cycle

A diurnal cycle is added to the Control simulation in order to investigate how the feedback loops identified in the Control and NoRecycle runs are modified with realistic transient heating and cooling tendencies due to variations in incoming shortwave radiation. A question that is addressed in this diurnal simulation is, to what extent is the continuous production of ice in the Control simulation due to the lack of incoming shortwave radiation, which may overestimate the cooling tendencies in the cloud layer, resulting in an overestimate of IN activation? In addition, we investigate whether allowing for a realistic diurnal cycle provides for additional buffering feedbacks.

Adding a diurnal cycle to the Control simulation produces a diurnal peak in downwelling surface shortwave radiation of 510 W m^{-2} and 6 hours of total darkness per day (Fig. 11b). As shortwave radiation increases, the net radiative cooling near cloud top diminishes, which decreases cloud-generated turbulence, decreasing LWP and cloud-layer thickness. In addition, it is seen that the peak daily LWP coincides with zero shortwave radiation when in-cloud turbulence and cloud thickness are largest (Fig. 11a). These values are on the low end but within the measurements for this ISDAC case.

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Fig. 11a,b shows that LWP and IWP variability is predominantly driven by the diurnal cycle. However, IWP variability is seen to lag LWP by 3-4 hours because as shortwave radiation decreases the cloud layer cools, which increases activation of IN, increasing N_{ICE}, allowing more ice crystals to grow, which increases IWP (Fig. 11a,b). Similar to the Control simulation subcloud N_{IN} decreases at a faster rate than cloud layer N_{ICE}, but allowing for the warming and cooling tendencies in the diurnal cycle results in cloud layer N_{ICE} that decreases 40% more slowly than in the Control simulation (Fig. 11c).

Precipitation and turbulent mixing of N_{ICE} (hereafter turbulent mixing is referred to as "T_{ICE}") at cloud base are out of phase by 10 hours (Fig. 11d), with turbulence leading precipitation. When shortwave radiation is weak or absent, the increase in N_{ICE} eventually becomes limited by a decreasing turbulent mixing of IN ("T_{IN}") into the cloud layer from below, as recycling slows due to a decrease in N_{ICE} flux from the cloud layer (Fig. 11d,f). When shortwave radiation is strong, reduction in IWP is limited by weaker precipitation losses, and attendant weaker sublimation and IN flux into the cloud layer (Fig. 11d,f). Entrainment of N_{IN} at the mixed-layer top is insignificant throughout the integration (Fig. 11e).

5 Analysis from a mixed-layer perspective

The results discussed in Section 4 can be understood from balances in a well-mixed layer with sources/sinks at the upper and lower boundaries. Total particle concentration (N_{IN}+N_{ICE}) is only changed by fluxes at the mixed-layer boundaries when recycling is allowed. These fluxes are entrainment of N_{IN} at mixed-layer top and turbulent mixing of both

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N_{ICE} and N_{IN} (T_{ICE} and T_{IN}) and precipitation of N_{ICE} (P) at mixed-layer base. Since there are no sources and sinks of N_{IN}+N_{ICE} within the mixed layer, the horizontally-averaged N_{IN}+N_{ICE} flux ($f(z)$) must vary linearly from mixed-layer base to mixed-layer top (Lilly, 1968; Bretherton and Wyant, 1997). If it is assumed that f at the mixed-layer base is downward (assumed negative in this formulation) and f at the mixed-layer top is negligible (robust assumptions for a scenario where ice is precipitating from the mixed layer and entrainment is weak), then

$$f(z) = R * \frac{H - z}{H - B}, \qquad B \leq z \leq H \tag{5}$$

where H is the mixed-layer height, B is the mixed-layer base and R is the total N_{IN}+N_{ICE} flux at the mixed-layer base,

$$R = f|_{\text{Mixed-Layer Base}} = [P + T_{ICE} + T_{IN}]_{\text{Mixed-Layer Base}}, \tag{6}$$

and

$$[T_{ICE} + T_{IN}]_{\text{Cloud Base}} \approx [f - P]_{\text{Cloud Base}}. \tag{7}$$

Since $f < 0$, the turbulent flux of N_{IN} into the cloud layer plus the turbulent flux of N_{ICE} into the subcloud layer is always less than precipitation of N_{ICE} at cloud base. In addition, in a slowly evolving state where $T_{IN}|_{\text{Mixed-Layer Base}} > 0$, total IN flux due to sublimation in the mixed layer, S, can be written as

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$$S \approx [P + T_{ICE}]_{\text{Mixed-Layer Base}} - [P + T_{ICE}]_{\text{Cloud Base}} \qquad (8a)$$

$$\approx [f - T_{IN}]_{\text{Mixed-Layer Base}} - [f - T_{IN}]_{\text{Cloud Base}} \qquad (8b)$$

and since $f|_{\text{Mixed-Layer Base}}$ is downward and $f|_{\text{Mixed-Layer Top}}$ is negligible (eq. 5),

$$S < T_{IN}|_{\text{Cloud Base}} - T_{IN}|_{\text{Mixed-Layer Base}} \qquad (8c)$$

$$< T_{IN}|_{\text{Cloud Base}} \,. \qquad (8d)$$

Thus in a well-mixed layer with an upward $T_{IN}|_{\text{Mixed-Layer Base}}$, sublimation is always less than the flux of N_{IN} into the cloud layer.

Based on results from Control, precipitation of N_{ICE} at cloud base is sufficient to balance the upward turbulent flux of N_{IN} (i.e., $|T_{IN}| \gg |T_{ICE}|$ at cloud base). Therefore, in a well-mixed layer with precipitation of N_{ICE} at the mixed-layer base that is larger in magnitude than an upward turbulent N_{IN} flux at the mixed-layer base, and assuming negligible entrainment at the mixed-layer top

$$|P|_{\text{Cloud Base}} > T_{IN}|_{\text{Cloud Base}} > S. \qquad (9)$$

However, if all N_{ICE} sublimate in the mixed layer and the upward turbulent flux of N_{IN} dominates at the mixed-layer base then $f > 0$ and

$$T_{IN}|_{\text{Cloud Base}} > |P|_{\text{Cloud Base}} = S, \qquad (10)$$

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the mixed layer gains $N_{IN}+N_{ICE}$ over time, resulting in a continuously increasing ice production in the cloud layer. In the presence of shortwave radiation (i.e., in the SW simulation), $T_{IN}|_{\text{Cloud Base}}$ is also greater than $|P|_{\text{Cloud Base}}$ after a period of weakened turbulence and weaker precipitation at the mixed-layer base, due to increased activation of N_{IN} due to decreasing shortwave radiation.

If IN entrainment at the mixed-layer top is not negligible then $f(z)$ must be modified to include fluxes at the mixed-layer top and $|f|_{\text{Cloud Base}}$ will increase. If $|f|_{\text{Cloud Base}}$ increases such that $f_{\text{Cloud Base}} < P_{\text{Mixed-Layer Base}}$, then sublimation will exceed $T_{IN}|_{\text{Cloud Base}}$.

This mixed-layer analysis provides a framework to understand the results presented in Section 4. Specifically, sublimation being less than the turbulent flux of IN is seen to be a property of a well-mixed layer where the total flux at mixed-layer base is downward and the total flux at the mixed-layer top is negligible. In the case where the mixed layer is saturated with respect to ice, sublimation is equal to zero and the turbulent flux of IN at the mixed-layer base is less that the turbulent flux of IN at the cloud base, reducing the flux of IN into the cloud layer. The relationships outlined in this section are appropriate for any AMPS with weak entrainment at cloud top, weak large-scale advective fluxes, and net downward fluxes at the mixed-layer base.

6 Analysis of Buffered Feedbacks in SW

Phase diagrams highlight the processes involved in ice production when a diurnal cycle is allowed (following the arrows from green to blue to black to red in Fig. 12a,b). When incoming shortwave radiation is a maximum, recycling (sublimation) is seen to be at a

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minimum. This is counterintuitive since subcloud relative humidity is low at this time, which would be expected to produce increased sublimation. However, due to weak turbulent mixing between the cloud and subcloud layers the net N_{ICE} flux into the subcloud layer is weak, resulting in weak sublimation and recycling. This situation is reversed as shortwave radiation decreases, since increased cloud-top cooling increases cloud-driven turbulent mixing, which allows recycling to increase in the regions of reduced subcloud relative humidity. As is seen in the conceptual diagram (Fig. 10), this then leads to an increased N_{ICE} flux into the subcloud layer (green arrows, Fig. 12). However, N_{ICE} in the cloud layer doesn't begin to increase until activation in the cloud layer exceeds the flux of N_{ICE} into the subcloud layer (green arrows). This cycle is further amplified as shortwave radiation decreases, namely, decreased shortwave radiation increases cloud-driven turbulence, increasing the flux of IN into the cloud layer, increasing the activation of IN, which increases N_{ICE} in the cloud layer and the N_{ICE} flux from the cloud layer into the subcloud layer (blue arrows).

When incoming shortwave radiation is a minimum, more N_{IN} are activated because the cloud layer cools. However, again we see that N_{ICE} tendencies due to thermodynamics are buffered by the slowing of turbulence-driven feedbacks due to a thickening of the cloud layer. Thus, a net increase in N_{ICE} in the cloud layer, commensurate with an increased IWP and precipitation (black arrows), is buffered by a decrease in the downward turbulent mixing of N_{ICE}, which reduces recycling, slowing the feedback loop (see Fig. 10). During the morning hours, as the cloud layer warms and thins and ice activation becomes less efficient, turbulence continues to decline, slowing the recycling feedback process to the point where limited IN fluxes to the cloud layer inhibit ice production and N_{ICE} declines (red arrows).

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7 Summary

We have demonstrated that sustained recycling of IN through a drying subcloud layer and additional activation of N_{IN} due to a cooling cloud layer are sufficient to maintain ice production, and regulate liquid production over multiple days in a decoupled AMPS.

This study provides an idealized framework to understand feedbacks between dynamics and microphysics that maintain phase-partitioning in AMPS. In addition, we have shown that modulation of the cooling of the cloud layer and the humidity of the subcloud layer by the diurnal cycle buffers the mixed-layer system from a loss of particles and promotes the persistence of a mixed-phase cloud system. The results of this study provide insight into the mechanisms and feedbacks that may maintain cloud ice in AMPS even when entrainment of IN at the mixed-layer boundaries is weak. While the balance of these processes changes depending upon the specific conditions of the cloud layer, for example whether the cloud layer is coupled to the surface layer, the mechanisms detailed in this paper will manifest to some degree and therefore the current study provides a framework for understanding the role of recycling in maintaining phase-partitioning in AMPS.

Author Contributions:

A.S., G.F., and M.D.S. conceived and designed the experiments; A.S. performed the simulations; A.S., G.F., and M.D.S. analyzed the model results and co-wrote the paper.

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Figure Captions

Figure 1: Sounding measured at 17:34 UTC 8 April 2008 at Barrow, Alaska (71.338N, 156.68W). Left) Water vapor mixing ratio (q_v), temperature (T), and potential temperature (Theta), in units of g kg^{-1}, degrees Kelvin, and degrees Kelvin respectively. Right) Zonal wind (U) and meridional wind (V), in units of m s^{-1}. Gray shading marks the extent of the cloud layer. The dashed lines show the initial profiles used in the WRFLES experiments. The dashed line overlaying water vapor mixing ratio is the initial profile for the total water mixing ratio.

Figure 2: IN number concentration active at water saturation vs. temperature based on the empirical relationship derived in DeMott et al. (2010) (blue line) used to initialize IN number concentration in each bin. Black vertical lines indicate threshold temperatures for nucleation in the 16 IN bins. IN increments between lines indicate the additional IN available for nucleation at colder temperatures.

Figure 3: Sensitivity of ice water path to the parameter F in equation (2). Note the similar ice water paths for F=4 and F=6 (total N_{IN} initial values 5.8 and 8.7 L^{-1}, respectively).

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Figure 4: A,B,D) Sensitivity of LWP and IWP to snow density and fall speeds. LWP shown with solid lines and IWP shown with dashed lines, in units of g m^{-2}. C) Fall speeds used in sensitivity studies, in units of m s^{-1}. A) Sensitivity to reducing snow density from 100 kg m^{-3} to 50 kg m^{-3} (red lines) using Control (CNT) fall speeds (red line in C). B) Sensitivity to reducing snow fall speeds (green line in C) using Control snow density (red lines). D) Sensitivity to increasing snow fall speeds (blue line in C) using Control snow density (red lines).

Figure 5: Simulated ice particle number size distributions using in-cloud mass and number concentrations. Ice water mixing ratio = 3e-4 g/kg, ice number concentration = 0.4/L, snow water mixing ratio = 2.4e-2 g/kg, snow number concentration = 0.45/L.

Figure 6: (A) N_{IN} and (B) N_{ICE} averaged over 0.5 hours at hour 20, in units of L^{-1} hr^{-1}. Grey shading indicates the extent of the cloud layer. Green dash lines indicate the top and bottom of the mixed layer.

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Figure 7: Time-height cross sections of horizontally-averaged (A) IN advection plus subsidence, in units of $L^{-1}hour^{-1}$, (B) ice plus snow number concentration, in units of L^{-1}, (C) water vapor mixing ratio, in units of g kg^{-1}, and (D) relative humidity with respect to ice, in units of percent, from CNT simulation. Temperature, in units of °C, shown with black contour lines in (B,C,D).

Figure 8: Control and NoRecycle time series for hours 6-40 (smoothed with 90 minute running average). NoRecycle shown with red and black dashed lines. A) LWP (black) and IWP (red), in units of g m^{-2}. B) Minimum horizontally-averaged temperature in the column, in units of ^{o}C. C) Mixed-layer depth (blue), top height (red), and base height (black), in units of km. D) N_{ICE} integrated over cloud layer (referred to as CL, red) and N_{IN} integrated over subcloud layer (referred to as SubCL, black), in units of m L^{-1}(i.e., meters/liter).

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Figure 9: Horizontally-averaged fluxes from Control and NoRecycle integrations for hours 6-40 (smoothed with 90 minute running average). NoRecycle shown with red and black dashed lines. A) N_{ICE} flux at cloud base due to turbulence+subsidence+precipitation (red), mixed-layer base due to turbulence+subsidence+precipitation (black), and due to activation (multiplied by -1, blue), in units of m L^{-1} hr^{-1}. B) N_{IN} flux at cloud base due to turbulence

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(red), N_{IN} flux due to sublimation (black), and precipitation of N_{ICE} at cloud base (multiplied by -1, blue), in units of m L^{-1} hr^{-1}. C) N_{IN} entrainment at mixed-layer top (red) and base (black), in units of m L^{-1} hr^{-1}.

Figure 10: Schematic of feedback loops that maintain ice production and the phase-partitioning between cloud liquid and ice in an AMPS. Red colors denote N_{IN}. Blue colors denote N_{ICE}. The size of the arrow indicates the relative magnitude of the flux. Vertical profiles of N_{ICE}, N_{IN}, relative humidity, and temperature shown with thin blue, red, green, and yellow lines, respectively.

Figure 11: A) LWP (black) and IWP (red), in units of g m^{-2}. (B) Downward surface shortwave radiation and turbulent kinetic energy (TKE) at cloud base, in units of Wm^{-2} and m^2s^{-2}, respectively. C) N_{ICE} in cloud layer (referred to as CL, red) and N_{IN} in subcloud layer (referred to as SubCL, black), in units of m L^{-1}. (D) Total, turbulent, precipitation N_{ICE} flux at cloud base (referred to as CL base, red, green, blue, respectively) and total N_{ICE} flux at mixed-layer base (referred to as ML base, black), in units of m L^{-1} hr^{-1}, for the SW integration for hours 16-76. Grey shading indicates hours with zero downwelling surface shortwave radiation. E) N_{IN} entrainment at mixed-layer top (red) and base (black), in units of m L^{-1} hr^{-1}. (F) N_{IN} flux at cloud base due to turbulence (red), N_{IN} flux due to sublimation (black), and activation of N_{ICE} (blue), in units of m L^{-1} hr^{-1}.

Figure 12: A) Phase diagram of TKE at cloud base vs. N_{ICE} in the cloud layer starting at peak shortwave hour 40, in units of m L^{-1} and m L^{-1} hr^{-1}, respectively. Colors show sublimation in units of m L^{-1} hr^{-1}. H) 24-hour phase diagrams of sublimation vs. minimum relative humidity in the subcloud layer starting at peak shortwave hour 40, in units of m L^{-1}

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hr^{-1} and %, respectively. Colors show total N_{ICE} flux at cloud base, m L^{-1} hr^{-1}. Hours 42-47, 47-50, 50-56, and 57-62 indicated with green, blue, black, red arrows, respectively. Minimum shortwave indicated with the moon symbol. Maximum shortwave indicated with the sun symbol.

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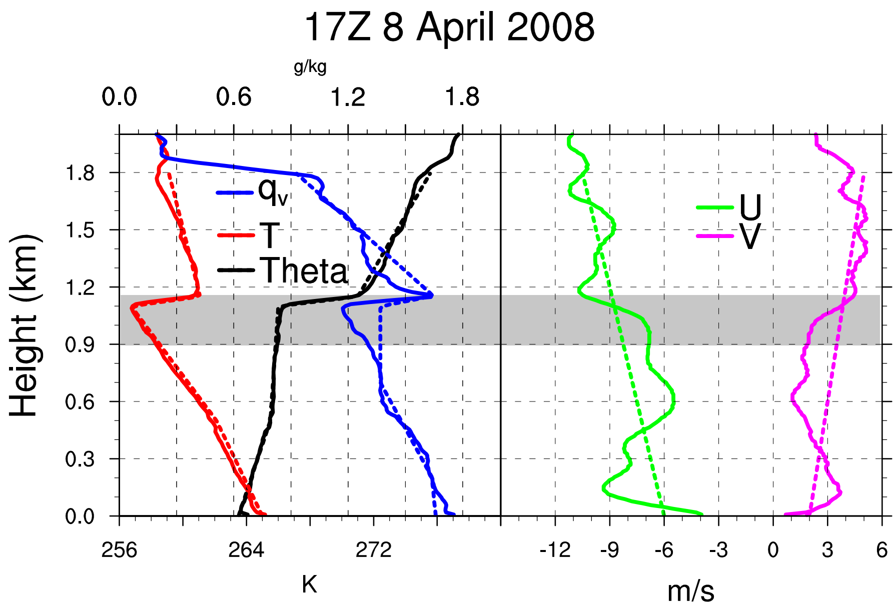

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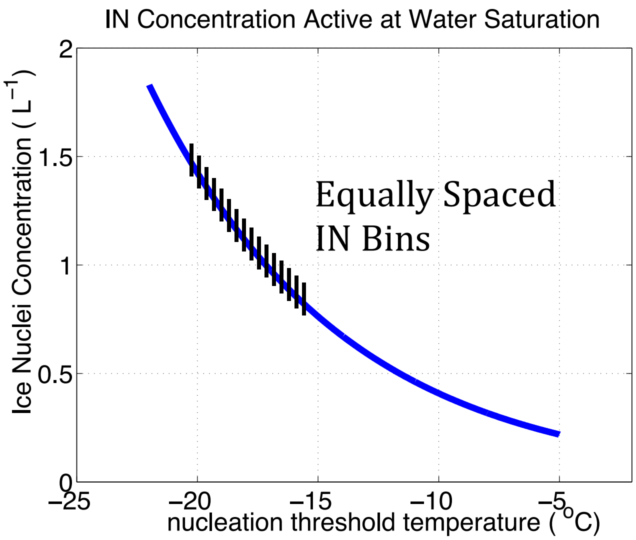

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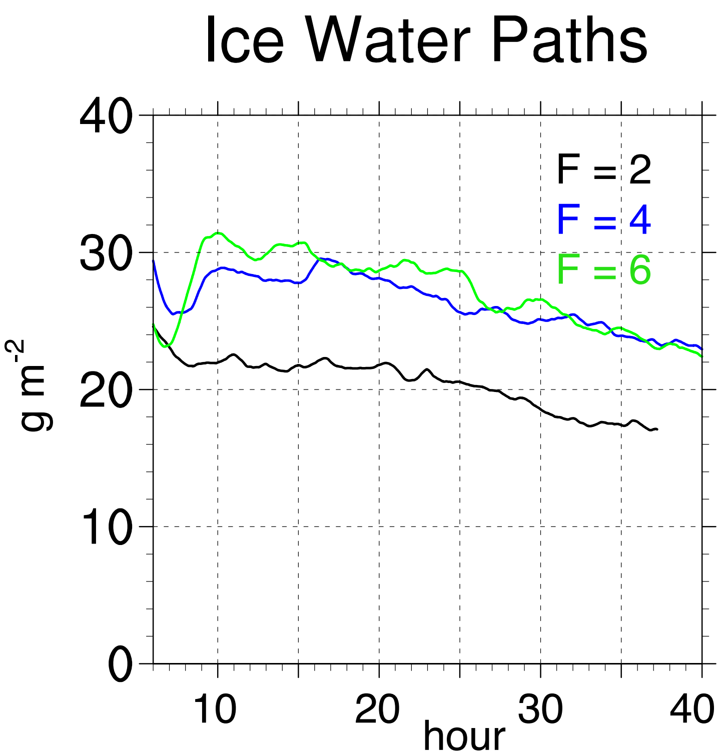

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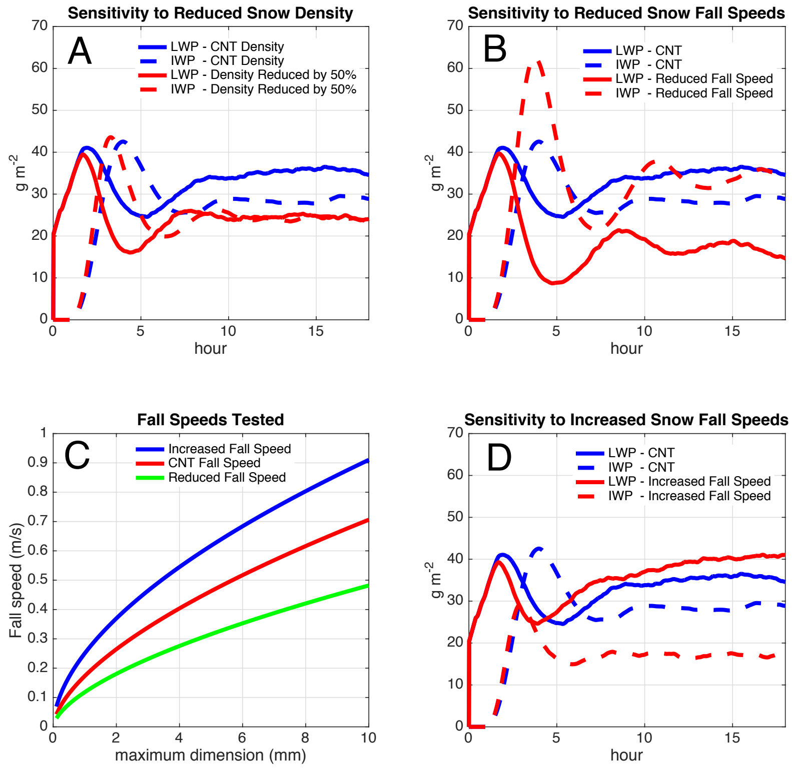

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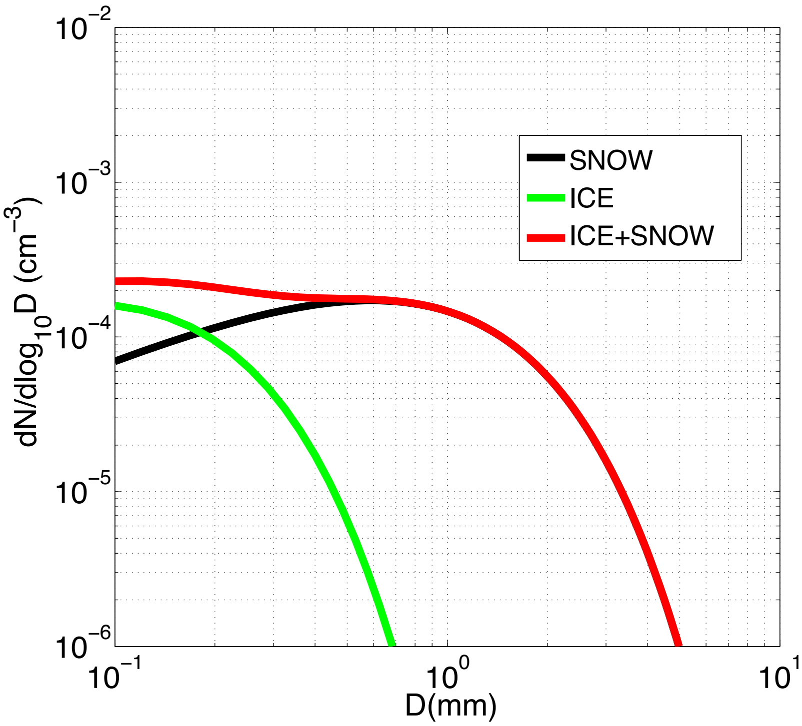

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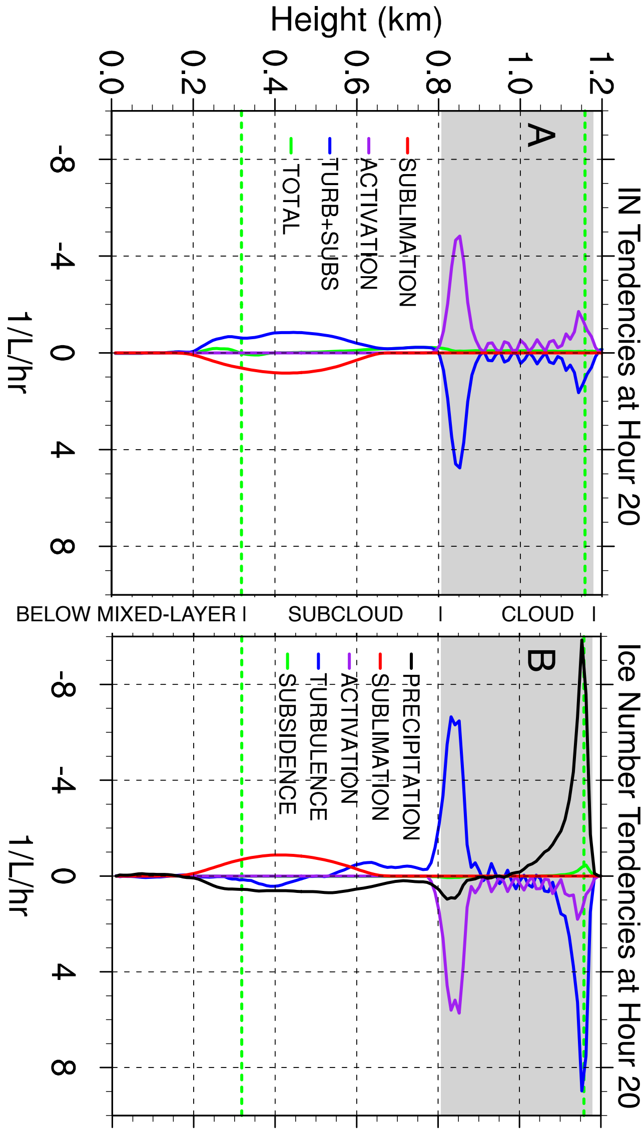

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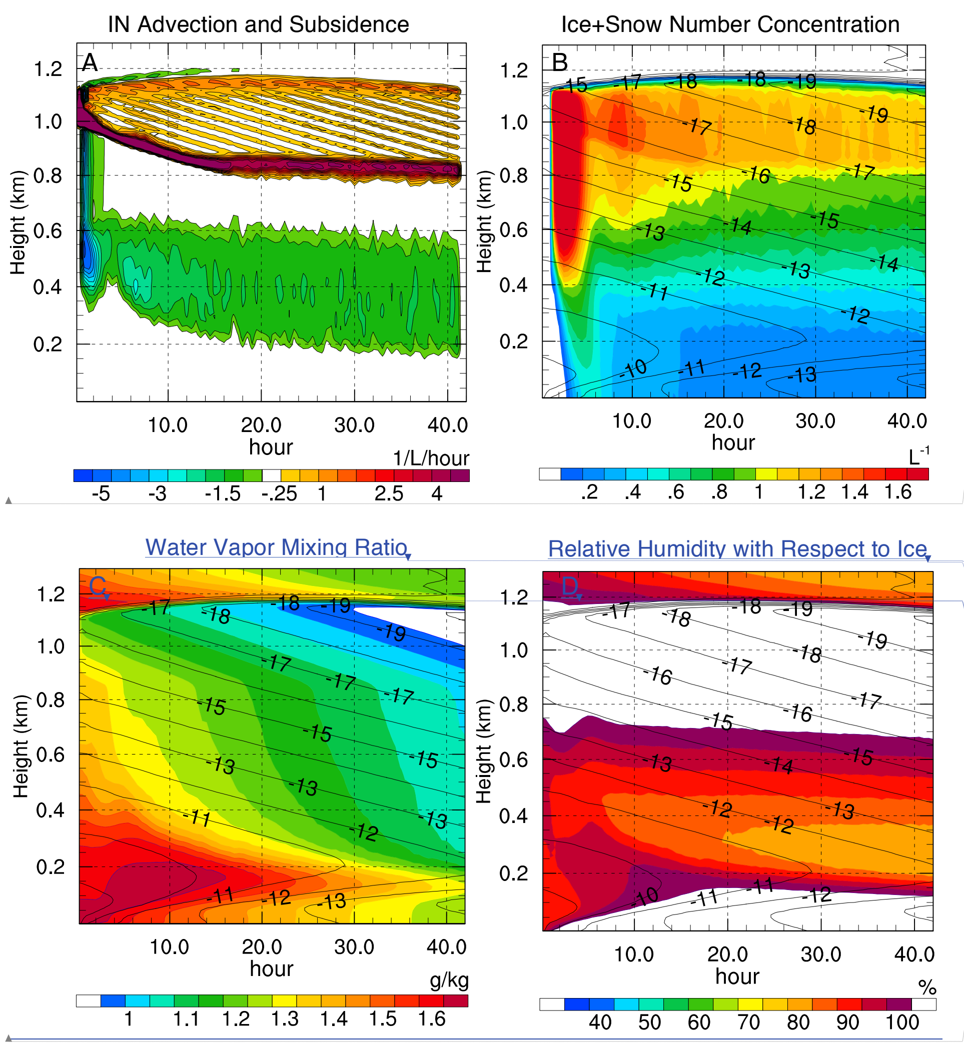

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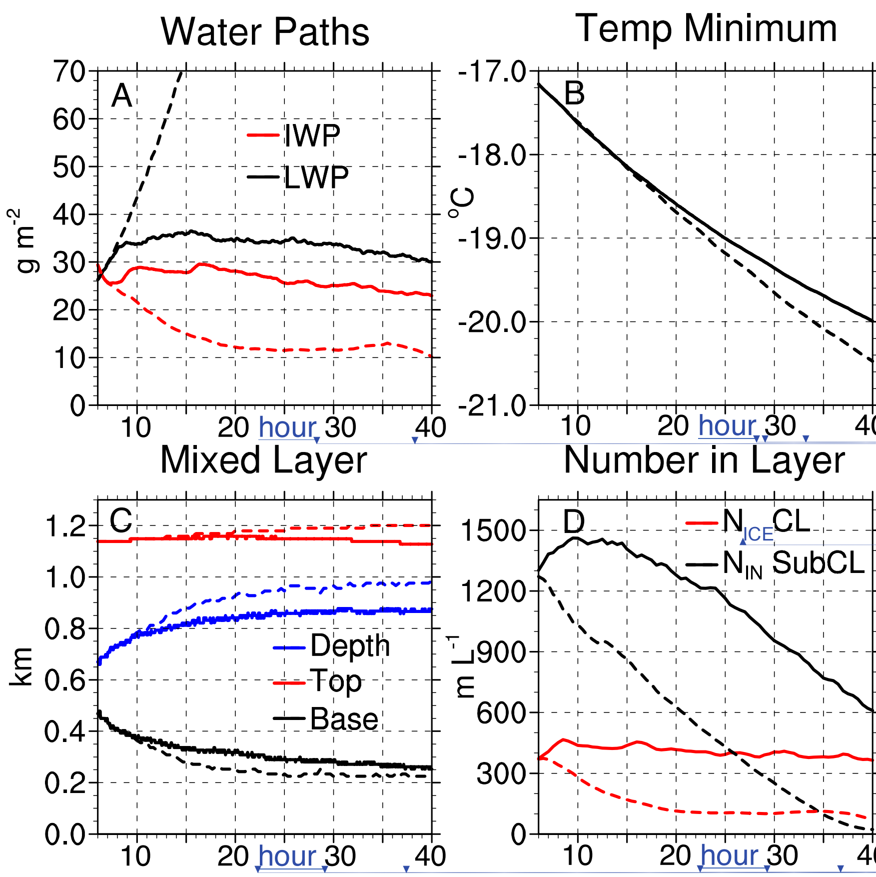

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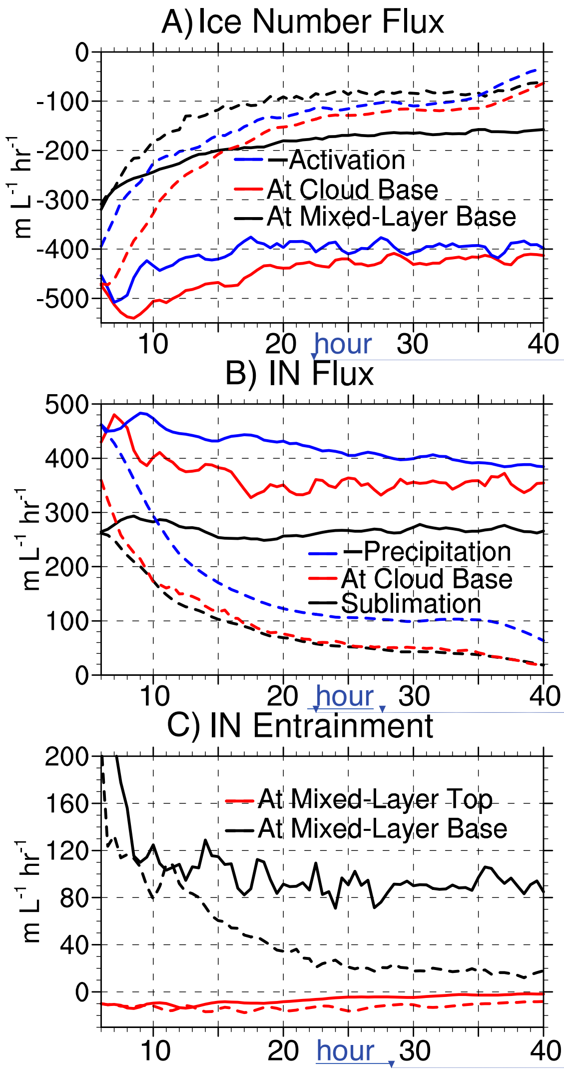

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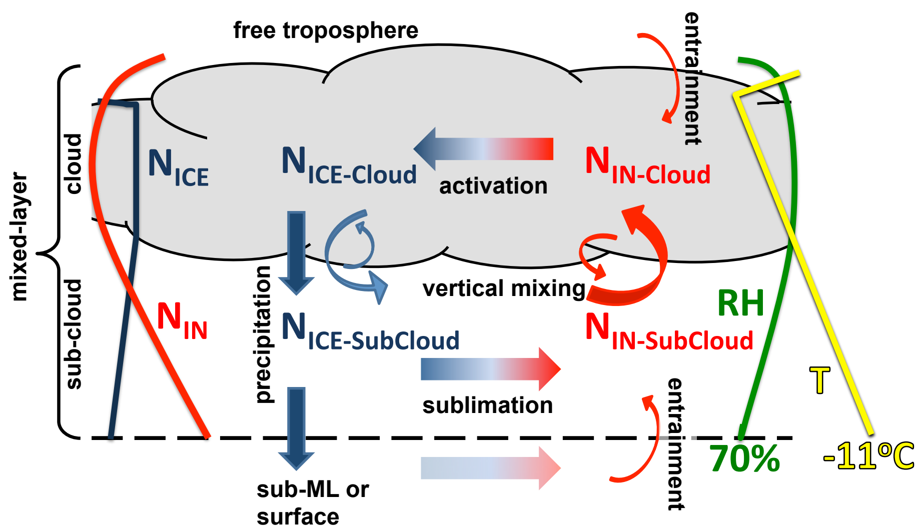

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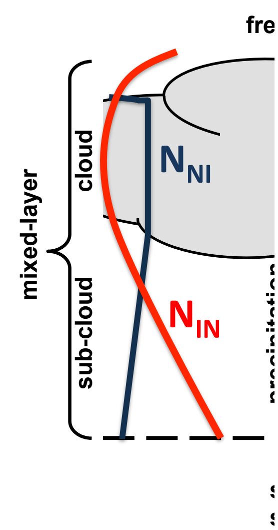

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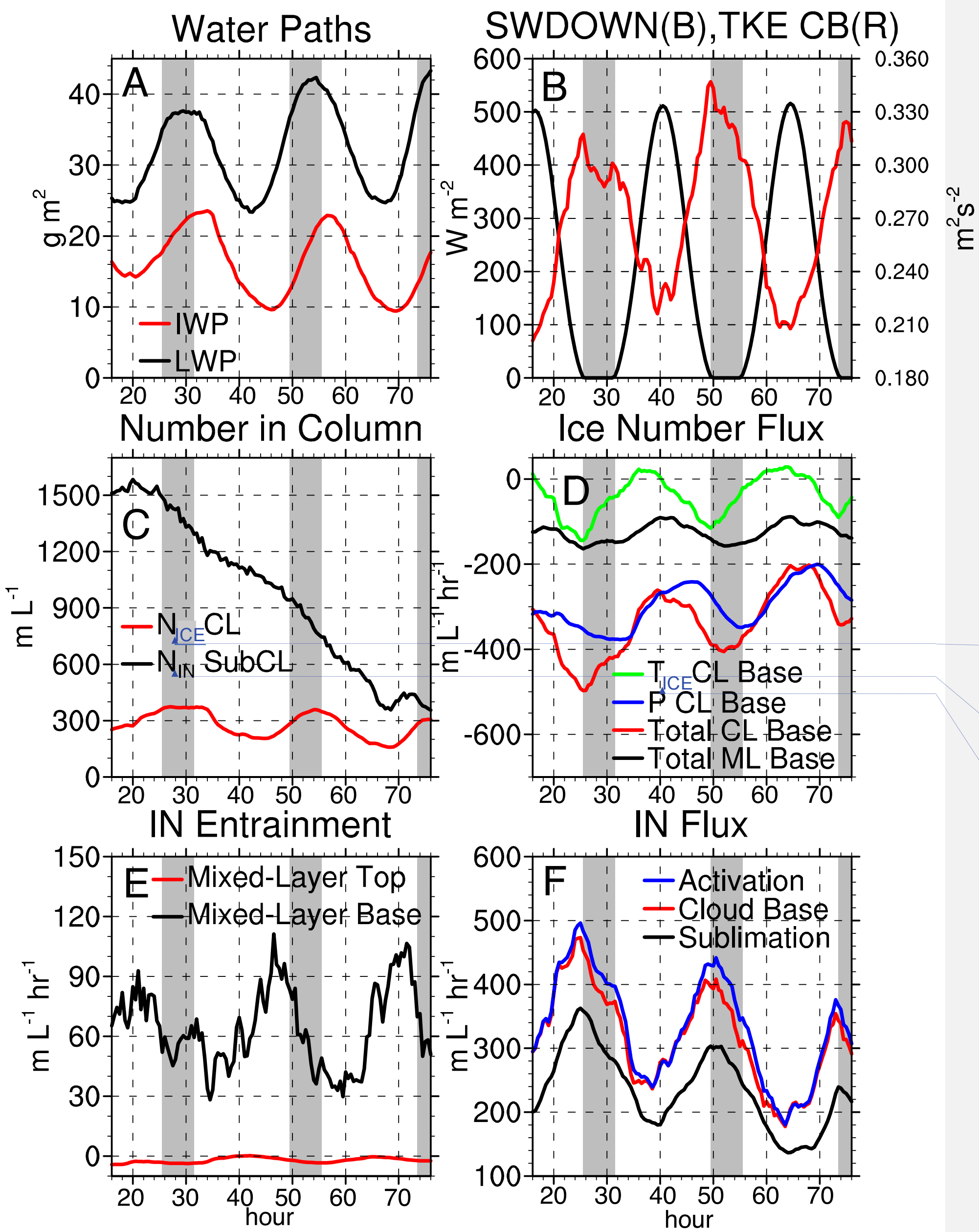

Figure 11: SW time series (see Figure captions).

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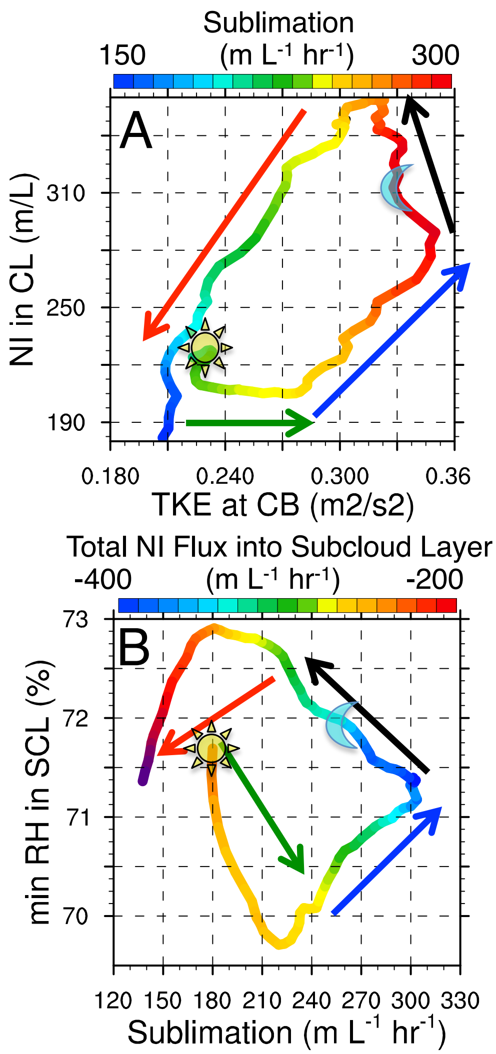

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