For clarity, reviewer comments are shown in normal font, response to reviewer comments are highlighted in yellow and **text edited** in the revised manuscript is shown in bold, underlined and highlighted.

**Reviewer 1:**

**1 Comments on presentation**

I am not an expert on arctic clouds, but globally, the question of LWP adjustments to Nd changes is extremely important in the context of rapid adjustments (formerly the "cloud lifetime effect") to the radiative forcing by aerosol–cloud interactions (formerly the "Twomey effect"). See, e.g., Gryspeerdt et al. (2019 ACP); Rosenfeld et al. (2019Science); Mulmenstadt and Feingold (2018 Current Climate Change Reports). It might help to make the connection to this literature in the introduction. As currently written, the introduction left me confused whether this is an aerosol–cloud paper (as the focus on Nd would suggest); or a feedbacks paper (as the statement about rapid warming would suggest); or a paper on the interaction between the two, in which case, perhaps cite Nazarenko et al. (2017 JGR) or Lohmann (2017 JGR) or an arctic equivalent, if that exists. However, from the main text, I think it's an ACI paper, so I would focus the introduction on LWP adjustments to the Twomey effect.

We would like to thank the reviewer for pointing out the confusion. We agree that connections to the literature should be clearer given the complex nature of cloud microphysical processes and their role for climate. As explained in more detail in the revised version of the manuscript, impacts of cloud microphysical processes on temperature trends are typically different for Arctic clouds than for clouds at lower latitudes. In particular, the Mauritsen limit is a proposed threshold for the aerosol concentration, where changes in the CCN (hence CDNC) results in net warming due to longwave effects, as referred to by Leaitch et al. (2016).

The focus of our paper is indeed aerosol-cloud interactions. Although the majority of the papers suggested by the reviewer focus on tropical and/or mid-latitude convection-based clouds, we have nevertheless added citations to the work of Mulmenstadt and Feingold (2018), Gryspeerdt et al. (2019), and Rosenfeld et al. (2019) in the introduction. We have also added more information about the cloud regime in question to the introduction, in hopes that it will help clarify the reviewer's confusion. The text now includes the following passages in the introduction:

Paragraph 1:

**"Microphysical properties of Arctic clouds are sensitive to changes in cloud condensation nuclei (CCN) concentrations (Coopman et al., 2018) as is cloud radiative effect (Rosenfeld et al., 2019)."**

Paragraph 1:

**"The present investigation involving the relationship between LWC and CDNC has also been found to vary geographically in other regions of the world (Gryspeerdt et al., 2019)."**

Paragraph 2:

**"Others have pointed out the inherent difficulty of reconciling the abstraction of autoconversion from the physical processes in the cloud as well (Mülmenstädt and Feingold, 2018)."**

and paragraph 3:

**“Recent observations by Leaitch et al. (2016) showed a strong linear relationship between LWC and CDNC in low altitude, relatively horizontally homogeneous, liquid clouds in the summertime Canadian Arctic with weak influences by outside mixing processes aside from the top and bottom of the clouds. The clouds were formed as air advected over cold water, rather than by lifting, and as such differ significantly from the adiabatic cloud concept model. In these clouds, LWC was approximately constant from the top of the cloud to the bottom of the observations, implying that the cloud did not form by lifting and condensation (Leaitch et al., 2016). The clouds were also persistent in time with no evidence of significant precipitation, hence likely in a quasi-equilibrium state.”**

We believe that these changes more clearly illustrate the relevance of the study to a broader discussion of the role of aerosol/cloud interactions in the climate system. More specifically, the goal of this paper is to contribute to this complex discussion by contributing to the knowledge of the nature of autoconversion in Arctic clouds during the NETCARE campaign.

Citations were also added for these papers.

The other major presentation question I had after reading the paper was what justified this focus on pure liquid clouds. Perhaps this betrays my ignorance, but I thought the most radiatively important low cloud type was mixed-phase in the Arctic, even in summer (Shupe and Intrieri, 2004?; de Boer et al., 2009).

Shupe and Intrieri (2004) found that “Overall, low-level stratiform liquid and mixed-phase clouds are found to be the most important contributors to the Arctic surface radiation balance,” so liquid water clouds are relevant in this environment. Additionally, many Arctic cloud papers are based around Utqiaġvik (formerly Barrow), Alaska, during the Arctic haze period, where mixed phase clouds are present, while our study is based near Resolute Bay, Nunavut, during July, where liquid clouds were prevalent.

**2 Comments on the analysis**

My main substantive concern is that I am not convinced the findings are statistically robust. If I understand the analysis correctly, the authors simulated 11 cloud profiles with different mean Nd and LWC. In the observations, cloud-mean LWC is proportional to cloud-mean Nd, based on these 11 data points. The authors then tried different micro-physical schemes to determine which one is best able to reproduce the observations. A setup without autoconversion gives the worst regression coefficient, and based on this, the authors conclude that autoconversion is responsible for the proportionality.

My concerns, in detail, are:

1. The no-autoconversion setup does pretty well, actually. It simulates higher LWC than the other setups, but that is to be expected, because a big sink process for LWC is turned off. The slope in Fig. 2 looks indistinguishable from the setups that are claimed to work better.

We have added the 95% confidence interval for the slope to Table 2: the “no rain” case has a larger variance, a lower $R^2$ value, and a larger interval than the other cases, suggesting that the appearance of the slope can be misleading on its own. We have also corrected the variance of the LWC column in Table 2, which was previously average variance. Nevertheless, we agree that there is relatively good agreement of model results with a few of the observations at CDNC > approx. 60 $cm^{-3}$ for the no-autoconversion setup, which provides evidence for the importance of the meteorological situation on the observed relationships beyond impacts of cloud microphysical processes on the LWC/CDNC relationship, as mentioned in the text. The model provides a tool for the quantification of these different influences on the LWC/CDNC relationship (Table 2).

2. The constant Nd runs also have pretty large slopes, which would indicate to me that a big part of the LWC increase is not due to autoconversion, or at least not due to the parameterized Nd dependence in the autoconversion rate.

The constant CDNC runs have low $R^2$ values and the "All CDNC 112/$cm^3$" case also has a large confidence interval, although the "All CDNC 5/$cm^3$" case does better by these measures than some of the schemes from the literature. We acknowledge that there are other processes affecting the LWC, and we do not expect the autoconversion to be the sole driver of the relationship. This is now emphasized in section 3.1 where we say:

"**Interestingly, simulations with the simplified parameterizations that do not account for effects of CDNC on autoconversion ('All CDNC 5/$cm^3$' and 'All CDNC 112/$cm^3$') also produce LWC values that are similar to the observed values for some of the flights, but have lower $R^2$ values compared to results with L&D and K&K parameterizations (see Table 2). However, the relative size of the 95% confidence interval from the 'All CDNC 112/$cm^3$' is large in comparison to the autoconversion cases and the observations (Table 2).**"

3. Continuing on that thought: in an attribution of an observed relationship to a candidate process, I would want to see some discussion on why other candidate processes are eliminated. Eliminating candidate processes is, of course, what models excel at, but confirming them, not so much (Oreskes et al. 1994, maybe?). First, I would want to know whether the clouds are adiabatic. Then, I would wantto know what stage in their life cycle they are in. At that point, a clearer picture may start to emerge; for example, in an adiabatic cloud, the vertically averagedLWC increases with cloud geometric thickness (thermodynamic conditions being equal), and the geometric thickness increases withNd(Pincus and Baker, 1994),purely from energy budget considerations.

Based on those concerns, I think a more convincing way to approach the problem would be first to build a conceptual model of the clouds and then to eliminate candidate processes (which probably requires numerical modeling), rather than to pick one process seemingly arbitrarily and trying to "confirm" it (because, as we know, science is the process of hypothesis refutation, not hypothesis confirmation).

The reviewer seems to be approaching the concept of the cloud as a typical updraft scenario with some vertical mixing due to cloud top cooling. However, although some of the higher-altitude clouds from the NETCARE campaign were formed from the more common lifting process, those discussed here were all low-altitude clouds with properties suggesting more similarities to advection fog. The introduction has been edited to clarify this point, and now states:

**"Recent observations by Leaitch et al. (2016) showed a strong linear relationship between LWC and CDNC in low altitude, relatively horizontally homogeneous, liquid clouds in the summertime Canadian Arctic with weak influences by outside mixing processes aside from the top and bottom of the clouds. The clouds were formed as air advected over cold water, rather than by lifting, and as such differ significantly from the adiabatic cloud concept model. In these**

**clouds, LWC was roughly constant from the top of the cloud to the bottom of the observations, implying that the cloud did not form by lifting and condensation (Leaitch et al., 2016). The clouds were also persistent in time with no evidence of significant precipitation, hence likely in a quasi-equilibrium state."**

Overall, we believe that key physical processes to the formation of the clouds are sufficiently accounted for in the simulations, as is also evident from the good agreement of model results with observations. Although the model is conceptually relatively simple, e.g. due to the omission of 3D transport processes, it is not obvious whether even simpler modelling frameworks exist that may also help to explain the observed relationships between LWC and CDNC.

My methodological comment is on letting the single-column model run to equilibrium. Actual clouds do not reach equilibrium, because precipitation acts as a condensate sink that (along with evaporation) causes the clouds to dissipate. In your method, the condensate loss by precipitation is balanced by moisture supply by advection, allowing the cloud to live forever. Clouds that live forever seem like a major limitation in a study on the cloud lifetime effect.

On the other hand, the model obviously needs to spin up.

This is a problem that the authors need to solve, but two suggestions they may find useful are:

1. Argue that clouds at any given point in time are in "quasi"-equilibrium. This is actually an assumption in many GCM parameterizations, i.e., the state the GCM tries to capture is representative of a cloud field averaged over a fairly long time step (30 minutes). However, I don't know if I would buy the argument for an individual cloud.

While the model is run to equilibrium, and the cloud at any point in time is not exactly at equilibrium, the clouds in question were highly persistent, indicating that the clouds were likely in quasi-equilibrium. We have noted the likely quasi-equilibrium state on lines 88-89, which state:

**"The clouds were also persistent in time, hence likely in a quasi-equilibrium state."**

Although we clearly do not address aerosol impacts on clouds or the cloud lifetime effect in our study, it should be emphasized that the model predicts the LWC and its response to autoconversion, which is a fundamental aspect of the Twomey effect. We also would like to clarify that the moisture budget in the simulation is a near-balance between surface fluxes, precipitation, and turbulent transport of moisture at the top of the cloud layer. For the shallow clouds that were observed, time scales of these processes are likely short relative to the time scale of advective transport into the cloud layer. The observations indicate that the clouds and atmospheric flow were fairly uniform over many tens of kilometres, so these assumptions seem justified. As such, it is not obvious to us that a fully prognostic 3D simulation of the observed cloud deck would necessarily produce much more realistic cloud vertical LWC profiles than a meteorologically highly constrained single column model.

2. Spin up the model with one Nd, then observe the transient behavior when you abruptly change to a different Nd. There is a series of papers by Andrew Gettelman (2015) on SCM studies of different cloud microphysics that might provide insight.

This is a very interesting suggestion but would require substantive work to do it justice and could be the focus of future work. We have added this in the conclusion, which now states:

**"It may also be of interest to compare these findings to a large-eddy simulation model. Another interesting future direction would be to probe our assumption that the cloud is in equilibrium. This could be accomplished by changing the CDNC abruptly after the model spin-up to observe the transient behaviour of the model microphysics, as performed by Gettelman (2015)."**

**Reviewer 2:**

This paper uses previously published observations (Leaitch ACP2016) of Arctic boundary layers of cloud liquid water content and droplet number to study the response of three autoconversion schemes and then considers the radiative properties of one cloud.

New data analysis demonstrates the linear relationship between cloud drop number concentration and liquid water path for these clouds which is a useful addition to the observational record. A number of samples in cloud were of low droplet number, in theCCN limited regime, referred to as the Mauritsen limit. Only very few samples were collected in this regime but the linear relationship appears to hold. As mentioned in the text, there is significant variability within the data, perhaps related to background meteorological conditions. It is therefore difficult to ascertain the significance of the result more broadly.

A main focus of the analysis and result is the comparison of three autoconversion schemes with the aim of investigating the impact of autoconversion on the LWP:CDNC relationship. All three of the autoconversion schemes appeared to perform well, suggesting that the process is in fact well constrained, even for the Arctic. The authors then demonstrate that a combination of two schemes, one for the CCN limited regime, and one for larger concentrations of CCN can improve on the performance of a single scheme across the full phase space. Again, the limited data makes this an intriguing but not completely satisfying result, with no attempt to explain, other than to invoke other processes such as turbulence and mixing.

Once the autoconversion schemes have been considered there is a section that investigates the radiative properties of clouds. The paper seems to lead towards a comparison of the radiative properties of clouds that are and are not CCN limited. However, only a cloud that is above this CCN limit is investigate, to the detriment of the work. Further, following the comparison of autoconversion schemes, these are shown to not have a large impact on the radiative properties of the clouds. The finding that the modelled radiation using the autoconversion schemes is different from observations in theJuly 8th cloud warrants further investigation and may be a useful result. Having only one such case though, is not likely to be sufficient to inform the modelling community of changes that might need to be made to the representation of aerosol indirect effects.

Numerous tables give details of the linear fit parameters, which whilst required, are not so easy to interpret. I would suggest that some measure of the uncertainty / significance is added to the plots to allow the reader to make an informed assessment. This would be useful on Figures 3, 4 and 5. It may also assist the reader to combine those panels in to a single figure. The aims of the paper should be more clearly stated, and in tandem the nature of the conclusions. The main conclusion seems to be that autoconversion is well prescribed, yet the radiative impacts of different schemes differ. It would be a great benefit to include the radiative impact of the clouds below the Mauritsen limit.

We would like to thank the reviewer for taking the time to provide their thoughtful comments. The reviewer's main concern seems to stem from the limited number of cases that were simulated, especially below the Mauritsen limit. We share these concerns, but are unfortunately limited by the data available from the study. It should be emphasized that this paper is not intended to serve as an overview of all that is possible in Arctic clouds. Instead, we can only examine a few low, liquid clouds that were observed to be persistent in the summer months when the Arctic is generally regarded to be quite pristine. We do extrapolate some larger conclusions from this small dataset about what is possible, but they are not intended as a limitation, but more of a broadening of possibilities and indication of avenues of future interests to see whether our results can be applied to other datasets or if they are more unique to the location. To emphasize the limitations of our study, we have reworded some of the text in the conclusion to read as follows:

**“It is important to note that our observations below the Maurtisen limit only consisted of 3 profiles and that our conclusions are dependent on this limited data set. It would be of interest to examine whether this regime change can be reproduced with more data, in other parts of the summer Arctic, and with other models.”**

Turbulence and mixing are complex processes with effects that are broad and difficult to quantify. We believe it is reasonable to assume that these processes are acting in the clouds in ways that are not well-represented by our models.

We did not model the radiative impacts of the clouds below the Mauritsen limit due to the limited number of vertical profiles in these clouds. Not only were there only three flight profiles into the clouds on July 5 and 7 in total, but also the solar zenith angle and surface albedo varied between these two flights as well as with July 8. Overall, this resulted in uncertainties that were too large to allow useful comparisons between all the profiles. This has now been clarified in Section 2.3; the text now reads:

**“Only profiles from July 8 are used for the radiative transfer calculations. The flights from July 5 and 7 were not analyzed due to the different solar zenith angles, the different surface albedos, the small number of available cloud profiles, and the possible effects of a different regime at lower CDNC. This resulted in uncertainties that would have made meaningful comparisons difficult.”**

To address the reviewer’s concerns about the figures, we have now grouped them together for easier reference, while preserving the higher quality images. We have also added the 95% confidence interval for the slope to tables 2 and 3, which will aid in the interpretation of the linear fit parameters. However, we believe that adding uncertainty or significance directly to the plots would add more visual confusion rather than lessen it and have not included this in our new figures.

**Reviewer 3:**

1. Is cloud droplet sedimentation (i.e. gravitational settling) included in SCM-ABLC? This should be explicitly stated, especially for the interpretation of the "no rain" case results. If not, then it is possible that this process would allow the model to better simulate the cases with the lowest CDNC values, due to the larger modelled cloud droplet sizes, regardless of which autoconversion scheme was used. For the case with a CDNC of 5 cm-3 in particular, the large modelled size of the cloud droplets could allow cloud droplet sedimentation to be significant, even in the absence of collision-coalescence processes to grow the cloud droplets to drizzle drop sizes. This should be discussed.

The reviewer brings up an important point. The cloud scheme in the SCM-ABLC does not include gravitational settling of cloud droplets. We have added the following sentence on lines 453-455:

**"Due to the lack of droplet sedimentation in the model, the droplets in the 'All CDNC 5/cm$^3$' case are likely to be very large, possibly resulting in more autoconversion than expected and lower LWC values in this simulation."**

2. Does the cloud vertical extent vary between simulations with different autoconversion schemes? Does the relationship between cloud vertical extent and CDNC differ between autoconversion schemes? The sensitivity test described on page 22 suggests that this could be important for shortwave radiative fluxes. This should therefore also be included in the discussion of aerosol indirect radiative effects on page 22.

Most of this process was originally described in section 2.3.2 in relation to the cloud profiles that were used for the radiative transfer model, but also applies to the discussion for Figure 2. We have added the following paragraph as section 2.2.6, and edited section 2.3.2 as not to be overly repetitious.

**"The cloud vertical extent produced by the SCM-ABLC can differ slightly between different autoconversion schemes, and does in some simulations. However, since the aircraft observations used in our comparisons do not include the entire cloud but only the uppermost part of it, we have focussed on comparing the thicknesses equivalent to the observed portion of the clouds rather than examining the modelled vertical extent. For each observed profile, we used the thickness of cloud measured down from the modelled cloud top to the penetration depth of the aircraft into the cloud during the NETCARE flights. Parts of cloud below the lowest flight level of the aircraft were omitted to avoid only relying on model output."**

3. I do not see any justification shown for the authors' inconsistent use of either p=0.01and p=0.05 as thresholds for significance. The use of different thresholds is most jarring in the abstract, on P21, lines 535-539, and on P21-22, lines 541-546. In all three locations, a value of $p>0.01$ is used to imply that no significant difference exists, and $p<0.05$ is used to imply that a significant difference does exist. I would suggest that if the authors have a justification for using a particular p value as the threshold for significance for this set of data, that it be included. If multiple different p value thresholds are used, this should be justified. Alternatively, the discussion of p-values could be rephrased such that statistical significance is not a binary value: p-values and significance would thus be treated similarly to the way that R^2 values and correlation are currently discussed in this and many other manuscripts.

We agree that it is confusing and we have elected to use p=0.05 as the threshold everywhere.

P2, lines 48-52: Changes in CDNC have also been linked to changes in cloud-top radiative cooling, which subsequently affects LWP through changes in cloud vertical thickness (e.g. Possner et al., 2017).

We have added a sentence to reflect this as well, as follows:

**"Depending on the amount of moisture in the free troposphere, changes in the CDNC may also positively or negatively affect the LWP via increased cloud top radiative cooling enhancing turbulent mixing and hence entrainment near the top of the cloud (Possner et al., 2017; Chen et al., 2015; Ackerman et al., 2004), or via precipitation."**

Citations were also added for these papers.

P4, lines 98-101: At least for the context of the observations, please offer a numerical value for the Mauritsen limit here. Also, the definition of the Mauritsen limit as "it is a proposed threshold for aerosol concentration, below which cloud droplets that form grow to sizes large enough to precipitate" is imprecise. Some cloud droplets will grow to sizes large enough to precipitate in many clouds with larger aerosol concentrations. And if it was true that below the Mauritsen limit all cloud droplets immediately grew to precipitation sizes, then no droplets would be observed in the cloud droplet size range. Please provide more precise definitions of the Mauritsen limit and the tenuous cloud regime. It might be helpful to define the tenuous cloud regime first, and to define the Mauritsen limit in that context.

We have added two previously-computed numerical values, as well as an explanation of the tenuous cloud regime and clarification of the Mauritsen limit on lines 99-108. The text now reads:

**"Mauritsen et al. (2011) proposed that a tenuous cloud regime exists when cloud formation is limited by the available CCN, wherein the low CDNC causes rapid growth from vapour deposition resulting in droplets large enough to fall. This was expanded by Leaitch et al. (2016), who introduced the Mauritsen limit as a threshold for the aerosol concentration, below which an increase in the CCN (hence CDNC) results in net warming due to longwave effects. As such, clouds with aerosol concentrations below the Mauritsen limit are presumed to be in the tenuous-cloud regime. Previously determined numerical values of the Mauritsen limit have included 10 $cm^{-3}$ (Mauritsen et al., 2011) and 16 $cm^{-3}$ (Leaitch et al., 2016), but the concept is not tied to specific droplet number concentrations as the environment can affect the threshold (Leaitch et al., 2016; Mauritsen et al., 2011)."**

P5, lines 146-147: For what reason is it expected that the number of larger droplets was negligible during these flights?

We concluded this based on the statistics presented by Leaitch et al. (2016) which reported that the 95$^{th}$ percentile of the volume mean diameter measured by the FSSP during low level clouds was 31 µm, which was far below the detection limit of 45 µm. The sentence in the paper now reads as follows:

**"However, we expect that the number of larger droplets was negligible in this work, as the 95$^{th}$ percentile volume mean diameter observed in low altitude clouds by Leaitch et al. (2016) was 31 µm, far below the upper size limit."**

Section 2.1: It would be helpful to give a description of any available observations of precipitation (or the absence thereof).

A PMS 2D-C greyscale probe present on the aircraft found no ice crystals or water droplets with diameter greater than 100 μm during the flights modelled in our study (Leaitch et al., 2016). We have included the following in the text in the paragraph before Section 2.1.1:

**"As per Leaitch et al. (2016), no ice crystals or water droplets with diameter greater than 100 μm were detected by the PMS 2D-C greyscale probe in any of these clouds, suggesting that these clouds were not precipitating. However, the low altitude clouds with very low droplet concentrations on July 5 and 7 had some droplets large enough in size (greater than 30 μm) that their settling speed was high enough to possibly be viewed as precipitation."**

P9, lines 241-243: This was not completely clear to me. Was the modification of the boundary-layer height an iterative process, requiring multiple simulations? Was the location of the LWC maximum in each time step compared to the location of observed LWC maximum, and the boundary-layer height adjusted online during a single simulation?

We agree that this was not clear in the original text. The section now reads:

**"For each case, the boundary layer height was estimated from the height of the base of the observed temperature inversion. The SCM-ABLC was then run for estimated modelled boundary layer heights within 30 m of that height. The height that resulted in a LWC profile most qualitatively similar to the observed was then used for all subsequent simulations for that case. The model LWC profile was averaged over the final 50 hours of the simulation and then used for all later runs for that case; the procedure was repeated for all cases."**

P11, lines 310-315: If aerosols were omitted in the radiative transfer calculations, then why were their optical properties computed? Also, please directly reference the parameterizations used for the optical properties.

We have removed the reference to aerosol calculations as we had indeed not calculated their optical properties. We have also added the references for the liquid water cloud optical property parameterizations. The text now reads:

**"Absorption by gases is computed using the correlated-*k* method (von Salzen et al., 2013; Lacis and Oinas, 1991). The optical properties of liquid clouds are computed using the parameterizations referenced by von Salzen et al. (2013), separately for solar (Dobbie, Li, and Chýlek, 1999) and infrared (Lindner and Li, 2000) wave numbers."**

and

"**Aerosols were omitted in the radiative transfer calculations due to their relatively small effects on the radiative fluxes compared to those due to the clouds."**

P13, line 370: This function cannot be correctly described as a linearization. It would be better to call it a piecewise function.

We thank the reviewer for pointing this out. This has been modified to now read:

**"Based on these results, we constructed a piece-wise function based on the two linearizations of the closest-fitting results to observations, called "L&D and K&K" corresponding to the combination of L&D and K&K schemes, with the K&K scheme at CDNC < 20/cm$^3$ and the L&D scheme at higher CDNC."**

P22, line 551: Considering the discussion of statistical significance that precedes it, a different word than “significantly” should be used here.

This has now been rephrased to read:

**“This may require further investigation as the L&D and Wood schemes differ only by a constant, while the K&K scheme uses an additional variable as well as different constants than those two.”**

Figures 2, 3: Would it be possible to have a single label for the corresponding lines and points in the legends? For example, could “Observations” be listed only once, with both the green line and green triangle? This would make the legends much clearer.

This has been done for all figures.

Technical corrections:
P1, line 21: “clouds,.” -> “clouds.”

Done.

P3, line 70: “consider the compare” please rephrase.

Done.

P9, line 246: please replace the dash after “SCM-ABLC” with a colon.

Done.

P9, line 257: please add a space after “ocean”.

Done.

P9, line 257: please add “implemented” after “As”.

Done.

P20, line 522: Perhaps it would be clearer to say “radiative transfer calculations” instead of “model runs”. The current phrasing leaves some ambiguity between the SCM-ABLC simulations (which are based on observations) and the radiative transfer calculations based on in-flight observations only.

Done.

**Additional Edits:**

The following modifications were made throughout the paper to improve the clarity and language:

**"Longwave/shortwave fluxes"** referring to the difference in those fluxes due to the cloud radiative effect throughout the paper have been better specified as **"longwave/shortwave cloud radiative effect"** or **"longwave/shortwave CRE."**

The current affiliation for Rashed Mahmood is now as follows (line 14): ***- Now at Barcelona Supercomputing Center, Barcelona, Spain**

Line 20-21: NETCARE -> **Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments**

Line 23 now reads: **"Of the three autoconversion schemes we examined, the scheme..."**

Lines 31-34 now read: **"In contrast, the downward longwave and shortwave cloud radiative effect at the surface for Wood and K&K schemes do not differ significantly (p=0.05) from the observation-based radiative calculations, while the L&D scheme differs significantly from the observation-based calculation for the downward shortwave but not the downward longwave fluxes."**

Line 41 now reads: **"As observed at other latitudes, for comparable liquid water content (LWC), ..."**

Lines 43-46 now read: **"However, the net radiative effect of cloud droplet size and number concentration can vary in sign in the Arctic due to the interplay between longwave and shortwave radiative effects when there are high surface albedo and large solar zenith angle (Curry et al., 1996)."**

Line 47: **"dominated"** -> **"controlled"**

Line 47-48: **"liquid water content"** -> **"liquid water path (LWP)"**

Line 49: removed **"Similarly,"**

Lines 50-51 now read: **"Model simulations without shortwave radiation have been used to show that it can..."**

Line 56: added **"e.g."** before the citation of Rosenfeld et al. (2014)

Line 73: added **"(three large eddy simulations and three numerical weather prediction models)"** to describe the models from the cited study.

Lines 79-82 now read: **"However, the study did not test different autoconversion parameterizations using the same model. Nor did the study compare the results of Arctic clouds with different CCN concentrations or rain formation schemes in the models (Stevens et al., 2018)."**

Line 106: **"keeping the CDNC"** -> **"the CDNC remains"**

Line 117-118: **"NETCARE"** -> **"Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments (NETCARE)"**

Line 118-119: **"cloud droplet number concentrations"** -> **"CDNC"**

Lines 133 & 136: removed **"will"**

Lines 138-139: **"relying on"** -> **"as it uses"**

Line 141: **"resulting"** -> **"that might result"**

Line 143: **"will be"** -> **"that are"**

Lines 144-146 now read: **"Changes in the radiative balance of the simulated clouds due to differences from the autoconversion schemes are examined using an offline version of the radiative transfer model in CanAM4.3"**

Lines 151-152: **"Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments (NETCARE)"** -> **"NETCARE"**

Lines 175-177 now read: **"(approximately 45 µm; Leaitch et al., 2016)"**

Line 186: **"2.2.1"** -> **"2.1.1"**

Lines 241-242: added **"Model results from the last 200 time steps, or 50 hours, were then averaged."**

Lines 252-253: **"cloud droplet number concentration"** -> **"CDNC"**

Line 290: replaced "-" with a colon

Line 301: added **"implemented"**

Lines 310-312 now read: **"The different representation of the autoconversion process in the L&D scheme results in stronger dependencies on LWC and CDNC"**

Line 320: added **"empirically-calculated"**

Lines 327-330 now read: **"All were originally developed for the mid-latitudes so as part of our study, we will be evaluating their performance in summer Arctic low clouds."**

Line 358: **"most important"** -> **"main"**

Lines 376-377: **"liquid water path (LWP)"** -> **"LWP"**

Lines 378-380: removed description and added **"as described in Section 2.2.6"**

Line 380: added **"again"**

Line 384: **“Section 3.3”** -> **“Section 3.2”**

Line 392: **“inputting”** -> **“setting”**

Line 400: added **“spanning”**

Line 418: added **“3.1 SCM-ABLC”** as a section header

Line 420: **“expected from”** -> **“observed by”**

Line 424: **“driver”** -> **“source”**

Line 443: added **“theoretical”**

Line 475: **“high observed”** -> **“greater”**

Lines 494-495: **“debatable”** -> **“likely dependent on the environment”**

Line 528: **“as the case with no autoconversion”** -> **“in this instance, since the no-autoconversion case”**

Lines 534-538: We removed references to studies about cumulous-type clouds, as they were inappropriate here.

Line 540: **“We also”** -> **“since we”**

Lines 541-543 now read: **“Future work may have to better incorporate subgrid-scale cloud mixing processes in models.”**

Line 545 now reads: **“3.2. Radiative fluxes”**

Line 551: **“cloud inputs from observations”** -> **“observed cloud properties”**

Lines 586-588 now read: **“Table 3. Summary of linear fits of radiation model CRE. See main text for description of cases.”**

Lines 594-597 now read: **“A similar decreasing linear relationship exists for the downward shortwave CRE at the surface (Figure 4). However, there is no significant difference at p=0.05 (see Table 4) in the downward shortwave CRE at the surface between each scheme and the observation-based radiative transfer calculations on July 8 except for the “L&D” and “All CDNC 5/cm$^3$” cases.”**

Lines 599-602 have been removed.

Lines 623-624 now read: **“the K&K scheme uses an additional variable as well as different constants than”**

Lines 645-646 now read: **“the three autoconversion parameterizations used in this study.”**

Lines 649-652 now read: **<u>"In particular, the change in shortwave CRE is much greater for the K&K parameterization than calculation based on observations, which is consistent with the particularly strong non-linear dependency of this parameterization on CDNC."</u>**

Line 666: **<u>"of the world where CDNC are higher"</u>** -> **<u>"with greater CDNC"</u>**

Line 675: added **<u>"which may also be interesting to reexamine with a larger dataset"</u>**

The following citations were also added:


Dobbie, J. S., Li, J., & Chýlek, P.: Two and four stream optical properties for water clouds and solar wavelengths. J. Geophys. Res., 104, 2067–2079, 1999.

Lindner, T. H., and Li, J.: Parameterization of the optical properties for water clouds in the infrared. J. Climate, 13, 1797–1805, 2000.

# Modelling the relationship between liquid water content and cloud droplet number concentration observed in low clouds in the summer Arctic and its radiative effects

Joelle Dionne[1], Knut von Salzen[2,3,4], Jason Cole[2], Rashed Mahmood[3,*], W. Richard Leaitch[2], Glen Lesins[1], Ian Folkins[1], Rachel Y.-W. Chang[1]

1- Physics and Atmospheric Science Department, Dalhousie University, Halifax, Canada

2- Climate Research Division, Science and Technology Branch, Environment and Climate Change Canada, Toronto, Canada

3- School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada

4- Earth, Ocean, and Atmospheric Sciences Department, University of British Columbia, Vancouver, Canada

Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, China*- Now at Barcelona Supercomputing Center, Barcelona, Spain

Correspondence to: R.Y.-W. Chang (rachel.chang@dal.ca)

**Abstract.** Low clouds persist in the summer Arctic with important consequences for the radiation budget. In this study, we simulate the linear relationship between liquid water content (LWC) and cloud droplet number concentration (CDNC) observed during an aircraft campaign based out of Resolute Bay, Canada conducted as part of the NETCARENetwork on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments study in July 2014. Using a single column model, we find that autoconversion can explain the observed linear relationship between LWC and CDNC. Of the three autoconversion schemes we examined, the autoconversion scheme using continuous drizzle (Khairoutdinov and Kogan, 2000) appears to best reproduce the observed linearity in the tenuous-cloud regime (Mauritsen et al., 2011), while a scheme with a threshold for rain (Liu and Daum, 2004) best reproduces the linearity at higher CDNC. An offline version of the radiative transfer model used in the Canadian Atmospheric Model version 4.3 is used to compare the radiative effects of the modelled and observed clouds,. ,.We find that there is no significant difference in the upward longwave fluxescloud radiative effect at the top of the atmosphere from the three autoconversion schemes (p=0.05), but that all three schemes differ at p=0.05 from the calculations based on observations. In contrast, the downward longwave and shortwave fluxescloud radiative effect at the

surface for ~~all three schemes~~ Wood and K&K ~~all three~~ schemes do not differ significantly (p=0.0~~1~~5~~01~~) from the observation-based radiative calculations~~.~~, while the L&D scheme differs significantly from the observation-based calculation for the downward shortwave but not the downward longwave fluxes.

## 1 Introduction

Observations show a warming trend in the Arctic that is 2.5 times greater than the rest of the world (ACIA, 2005). One known uncertainty in our understanding of climate change is the effect of clouds on the radiation budget (Lohmann and Hoose, 2009), with particularly important consequences for Arctic climate. Microphysical properties of Arctic clouds are sensitive to changes in cloud condensation nuclei (CCN) concentrations (Coopman et al., 2018) as is ~~,~~cloud radiative effect (Rosenfeld et al., 2019). ~~Like~~As observed at other latitudes, for comparable liquid water content (LWC), smaller cloud droplets in the Arctic are associated with less shortwave radiation at the surface than larger droplets due to an increased reflectivity (Peng et al., 2002). However, the net radiative effect of cloud droplet size and number concentration can vary in sign in the Arctic ~~when combining the~~due to the interplay between longwave and shortwave radiative effects when there are ~~because of the~~ high surface albedo and large solar zenith angle (Curry et al., 1996). Overall, the radiative forcing from shortwave radiation due to cloud is ~~dominated~~controlled by cloud microphysical properties such as liquid water ~~content~~path (LWP~~C~~), effective radius, cloud droplet number concentration (CDNC), as well as solar zenith angle, and surface albedo (Curry et al., 1996). ~~Similarly, t~~The longwave cloud radiative forcing is dominated by LWC, effective radius, phase, and emission temperature of the cloud (Sedlar et al., 2010). ~~In addition, m~~Model ~~runs~~simulations without shortwave radiation have been used to show~~n~~ that it can also impact Arctic stratus clouds by limiting their height as well as microphysical properties, demonstrating feedbacks between radiation and cloud properties (Olsson et al., 1998). In general, the impact of increasing the CDNC is more complicated than just reducing the cloud droplet size and increasing the cloud reflectance, as it may inhibit precipitation, cause smaller droplets to evaporate faster in non-precipitating clouds, and/or suppress the breakup of clouds by precipitation (e.g. Rosenfeld et al., 2014). Depending on the amount of moisture in the free troposphere, changes in the CDNC may also positively or negatively affect the LWP via increased cloud top radiative cooling enhancing turbulent mixing and hence entrainment near the top of the cloud (Possner et al., 2017; Chen et al., 2015; Ackerman et al., 2004), or via precipitation. The present investigation involving the relationship between LWC and CDNC has also been found to vary geographically in other regions of the world (Gryspeerdt et al., 2019).

In cloud models, an important parameterization that affects the cloud microphysical properties, and thus cloud lifetime and radiative effects, is the autoconversion scheme, which converts cloud droplets to drizzle drops in order to simulate rain. These schemes are usually used instead of explicit calculations of the cloud droplet size distribution to reduce the computational cost and complexity of models. Autoconversion schemes can depend on variables such as cloud LWC, air density, CDNC, and droplet radius. Some have a threshold below which the cloud does not simulate rain while others simulate continuous precipitation based on LWC. Autoconversion rates from different parameterizations can vary from $10^{-7}$ to $10^{-11}$ kg $m^{-3}$ $s^{-1}$ for marine boundary layer clouds (Wood, 2005b), so the choice of autoconversion scheme can be significant. A recent study compared the output of six models (three large eddy simulations and three numerical weather prediction models) simulating clean Arctic conditions, showing that under very clean conditions, clouds can be very sensitive to cloud condensation nuclei (CCN) concentrations, with otherwise-identical simulations from individual models producing different cloud properties, to the point that the LWC and radiative effects of the clouds were CCN-limited (Stevens et al., 2018). In that study, models with faster autoconversion rates were found to be generally less sensitive to changes in CDNC or CCN concentrations for all examined cloud properties. However, the ~~model simulations~~study did not ~~allow~~test different autoconversion parameterizations ~~to be compared~~ using the same model. ~~Furthermore, that~~Nor did the study ~~did not consider the~~ compare the results of Arctic clouds with different CCN concentrations or rain formation schemes in the models (Stevens et al., 2018). Others have pointed out the inherent difficulty of reconciling the abstraction of autoconversion from the physical processes in the cloud as well (Mülmenstädt and Feingold, 2018).

Recent observations by Leaitch et al. (2016) showed a strong linear relationship between LWC and CDNC in low altitude, relatively horizontally homogeneous, -liquid clouds in the summertime Canadian Arctic with weak influences by outside mixing processes aside from the top and bottom of the clouds. The clouds were formed as air advected over cold water, rather than by lifting, and as such differ significantly from the adiabatic cloud concept model. In these clouds, LWC was approximately constant from the top of the cloud to the bottom of the observations, implying that the cloud did not form by lifting and condensation (Leaitch et al., 2016). The clouds were also persistent in time with no evidence of significant precipitation, hence likely in a quasi-equilibrium state. Instead of droplet size reducing with increasing CDNC, the volume mean diameter remained approximately constant, with a value near 20 µm (Leaitch et al., 2016). Three possible physical explanations for the linear relationship between LWC and CDNC are discussed here. One possible cause is autoconversion, since the autoconversion of cloud water becomes less efficient at higher CDNC because relatively fewer droplets are converted to rain drops, so the liquid in them stays as LWC rather than precipitating out, leading to higher cloud LWC (Albrecht, 1989). A second possible cause is the entrainment of dry air parcels into a cloud without mixing with the cloud droplets. This type of inhomogeneous mixing occurs when the evaporation timescale is shorter than the timescale to mix the entrained parcels within the cloud, which results in some droplets evaporating fully in and near the entrained parcel, lowering the CDNC as well as the LWC (Gerber et al., 2008; Jensen et al., 1985), which may lead to a nearly linear relationship between LWC and CDNC. In contrast, during homogeneous mixing, the evaporation timescale is longer than the mixing timescale, which results in most cloud droplets losing some water, but not completely evaporating, thus lowering the LWC while ~~keeping~~ the CDNC remains constant. During one of the flights, Leaitch et al. (2016) noted that entrainment appeared to reduce the CDNC, but not the LWC, which is inconsistent with the linear change observed overall. As such, while entrainment may be a possible driver of the linearity of the LWC-CDNC relationship on the other days, it is likely not the sole or main driver overall in our dataset. A final possible cause is increased rates of cooling causing increased rates of condensation (and possibly supersaturation), which increases both the CDNC and LWC. A possible mechanism for this would be fog advecting over a colder surface, as when a water temperature gradient exists. The implication of autoconversion driving part of the observed linear relationship is that it provides evidence for the second aerosol indirect effect since higher CDNC suppress rainfall, leading to higher LWC.

Three of the cases observed during the ~~NETCARE~~Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments (NETCARE) 2014 flight campaign had ~~cloud droplet number concentrations~~ CDNC at or below the tenuous cloud regime (Leaitch et al., 2016; Mauritsen et al., 2011). ~~Termed the Mauritsen limit by Leaitch Termed t by Leaitch et al. (2016), it (2016), it is a proposed threshold for aerosol concentration, below which cloud droplets that form grow to sizes large enough to precipitatebelow which cloud droplets that form grow to sizes large enough to precipitate.~~ Mauritsen et al. (2011) proposed that a tenuous cloud regime exists when cloud formation is limited by the available CCN, wherein the low CDNC causes rapid growth from vapour deposition resulting in droplets large enough to fall. This was expanded by Leaitch et al. (2016), who introduced the Mauritsen limit as a threshold for the aerosol concentration, below which an increase in the CCN (hence CDNC) results in net warming due to longwave effects. As such, clouds with aerosol concentrations below the Mauritsen limit are presumed to be in the tenuous-cloud regime. Previously determined numerical values of the Mauritsen limit have included 10 $cm^{-3}$ (Mauritsen et al., 2011) and

16 $cm^{-3}$ (Leaitch et al., 2016), but the concept is not tied to specific droplet number concentrations as the environment can affect the threshold (Leaitch et al., 2016; Mauritsen et al., 2011).

In this study, we ~~will~~ attempt to reproduce the observed linear relationship between LWC and CDNC using the Single Column Model for Arctic Boundary Layer Clouds (SCM-ABLC), which is based on the fourth generation of the Canadian Atmospheric Global Climate Model (CanAM4) (von Salzen et al., 2013). Specifically, we ~~will~~ examine whether autoconversion can explain the observed linear relationship between CDNC and LWC, since the SCM-ABLC does not include radiative feedbacks involved in increasing condensation rates or parameterizations of inhomogeneous mixing~~, relying on~~ as it uses a first order turbulence closure. Dry air above the cloud is allowed to mix into the cloud and evaporate cloud droplets, but this parameterization may not be sufficient to accurately account for the effect of stirring between cloudy and non-cloudy air, that might result~~ing~~ in inhomogeneous mixing (Gerber et al., 2008; Jensen et al., 1985). The simulated CDNC and LWC using three autoconversion schemes (Wood, 2005b; Liu and Daum, 2004; Khairoutdinov and Kogan, 2000) that ~~will b~~are explored and compared. Changes in the radiative balance of the simulated clouds due to~~We will also examine if the~~ differences from the autoconversion schemes are examined ~~significantly change the radiative balance of the simulated cloud by~~ using an offline version of the radiative transfer model in CanAM4.3 (see Section 2.3 for details).

## 2. Methods

### 2.1. Observations

This study uses observations from the ~~Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments (~~NETCARE~~)~~ project (Abbatt et al., 2019). These data were collected during an aircraft campaign on board the Alfred Wegener Institute's Polar 6 aircraft based out of Resolute Bay, Nunavut (74º40′48″ N, 94º52′12″ W), in July 2014 (see Figure 1). Only details relevant to this study are included below. A more extensive description of the details of the flight campaign can be found in Leaitch et al. (2016).

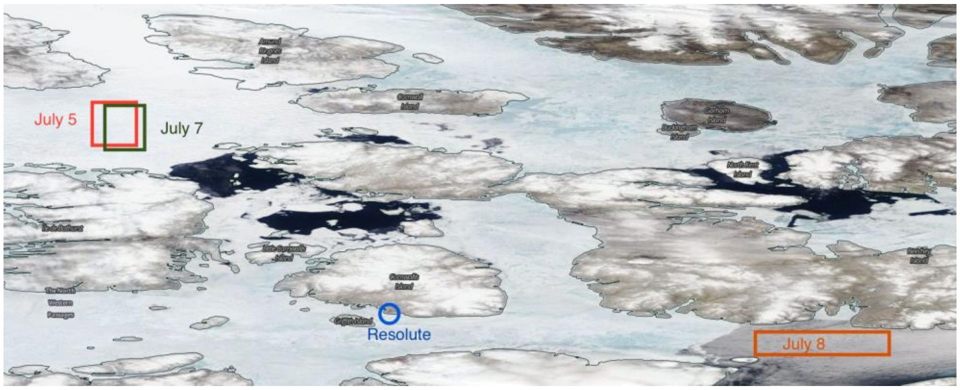


Figure 1. Satellite image from July 8, 2014 depicting Resolute Bay and the surrounding area, with rectangles showing the approximate locations of profiles on July 5, 7, and 8. Retrieved from https://worldview.earthdata.nasa.gov/

Temperature, wind speed, and relative humidity measurements from the Aircraft Integrated Meteorological Measurement System (AIMMS-20) were used in the creation of input profiles for the SCM-ABLC. Cloud properties were determined from the Forward Scattering Spectrometer Probe (FSSP-100, Particle Measuring Systems), which measured the number concentration and size distribution of cloud droplets, allowing the LWC and CDNC to be determined. The FSSP was mounted in a canister under the port-side wing (Leaitch et al., 2016), with modified tips to reduce shattering artifacts as per Korolev et al. (2011). These data were processed to account for the geometry of the FSSP (depth of field = 0.298 cm, beam diameter = 0.02 cm and the true air speed from the AIMMS-20). No corrections were applied for probe dead-time or for coincidence effects since these were deemed to be negligible due to the low airspeed of the aircraft (~65 m/s) and low CDNC (< 131/cm$^3$) in this study, respectively. However, LWC may be underestimated due to droplets that were larger than the upper limits of the chosen FSSP sampling sizes (approximately 45 µm; Leaitch et al., 2016)~~, which were sometimes set below the upper detection limit of the FSSP. It is also possible that some droplets were larger than the actual upper detection limit of the FSSP of 45 µm (Leaitch et al., 2016)~~. However, we expect that the number of larger droplets was negligible in this work, as the 95$^{th}$ percentile volume mean diameter observed in low altitude clouds by Leaitch et al. (2016) was 31 µm, far below the upper size limit. As per Leaitch et al. (2016), no ice crystals or water droplets with diameter greater than 100 µm were detected by the PMS 2D-C greyscale probe in any of these clouds, suggesting that these clouds were not precipitating. However, the low altitude clouds with very low droplet concentrations on July 5 and 7 had some droplets large enough in size (greater than 30 μm) that their settling speed was high enough to possibly be viewed as precipitation.

### *2.21.1. Vertical Profiles*

Flight sections through and near low clouds (defined as cloud top height ≤ 220 metres) from July 5, 7, and 8, 2014 were included in this study and the profile locations and times chosen are shown in Table 1. Each profile contains a single trip either up or down by the aircraft and were chosen for segments when observations existed for at least 20 m in and above the cloud. Additionally, data points were excluded when any one of the instruments collecting the data that went into the input profiles malfunctioned. As many profiles as possible from the Leaitch et al. (2016) study were included in this study. However, profiles either through very thin cloud layers or entirely within a cloud layer without any observations above the cloud were excluded.

| Date July 2014 | Start Time (UT) | End Time (UT) | Lowest Cloud Altitude Bin (m) | Highest Cloud Altitude Bin (m) | Mean CDNC (/cm$^3$) | Starting Latitude | Ending Latitude | Starting Longitude | Ending Longitude |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 16:17:09 | 16:18:31 | 100 | 130 | 5.5 | 77.3284 | 77.2796 | -98.7378 | -98.8190 |
| 7 | 16:20:54 | 16:26:58 | 90 | 150 | 15 | 77.1818 | 77.3280 | -98.4485 | -98.8793 |
| 7 | 16:26:59 | 16:28:54 | 80 | 110 | 17 | 77.3273 | 77.2580 | -98.8786 | -98.7206 |
| 8 | 17:27:20 | 17:29:02 | 140 | 190 | 96 | 74.1878 | 74.1895 | -87.8455 | -88.0827 |
| 8 | 17:29:03 | 17:29:57 | 150 | 200 | 87 | 74.1895 | 74.1916 | -88.0851 | -88.2086 |
| 8 | 17:31:29 | 17:32:16 | 150 | 190 | 70 | 74.2006 | 74.2046 | -88.4050 | -88.5083 |
| 8 | 17:32:17 | 17:33:00 | 150 | 200 | 49 | 74.2047 | 74.2090 | -88.5105 | -88.6061 |
| 8 | 17:35:00 | 17:35:43 | 150 | 190 | 100 | 74.2313 | 74.2401 | -88.8686 | -88.9604 |
| 8 | 17:35:44 | 17:36:22 | 150 | 210 | 114 | 74.2403 | 74.2471 | -88.9626 | -89.0419 |
| 8 | 17:38:25 | 17:39:12 | 150 | 220 | 105 | 74.2712 | 74.2816 | -89.3039 | -89.4023 |
| 8 | 17:43:29 | 17:44:43 | 150 | 200 | 93 | 74.3361 | 74.3520 | -89.9603 | -90.1210 |

Table 1. Details of the location and time of the low clouds examined in this study.

Our model represents spatially-averaged conditions in cloudy and clear-sky grid cells separately for a better comparison with observations, so non-cloudy samples were removed before averaging data points in cloudy grid cells. This was accomplished by binning LWC data points in each profile into 10 metre altitude bins. Bins were then categorized as being in cloud if more than 50% of the LWC data points were greater than 0.01 g/m$^3$. For bins deemed to be in cloud, only individual data points within each in-cloud bin with LWC greater than 0.01 g/m$^3$ were included in the bin's average LWC. A similar procedure was applied to altitude bins considered to be out of cloud, but with a condition that the average and individual LWC had to be less than 0.01 g/m$^3$ in order to be included. Meteorological variables were also averaged into altitude bins, but only observations associated with LWC values included in the bin average were included in the analysis.

The SCM-ABLC only used a single input of CDNC for each profile. As such, a mean CDNC was calculated throughout the observed portion of the cloud by averaging the CDNC corresponding to each LWC data point in the in-cloud altitude bins over the number of data points in that bin. An average over all of the in-cloud altitude bins was then calculated and used as a fixed input in the SCM-ABLC. This two-step averaging procedure accounted for potential bias from the length of time the aircraft flew at each altitude.

## 2.2. SCM-ABLC

### *2.2.1 Cloud Physics and Processes*

Much of the model physics of the SCM-ABLC, from cloud processes and turbulence to the parameterizations of the ocean surface, is taken from the Canadian Atmospheric Global Climate Model, CanAM4 (von Salzen et al., 2013). However, the SCM-ABLC only models liquid clouds, excluding ice and mixed-phase clouds, and does not include aerosol processes. Clouds are produced by local turbulent mixing processes, which move moisture, heat, and momentum down-gradient, and are affected by surface fluxes. Cloud microphysical processes are prognostic using a scheme based on the governing equations for water vapour and cloud liquid water outlined in Lohmann and Roeckner (1996) and Lohmann (1996) (von Salzen et al., 2013).

Eddy diffusivities calculated in the model depend on horizontal wind, height above ground, the gradient Richardson number, and a mixing length (von Salzen et al., 2013). In the presence of cloud, the mixing length is set to 100 metres (von Salzen et al., 2013), while in the absence of cloud, the mixing length is calculated from the parameterization by Lenderink and Holtslag (2004). Surface fluxes, including evaporation from the ocean, as well as heat and momentum fluxes, are simulated using an approach based on Monin-Obukhov similarity theory (von Salzen et al., 2013).

The vertical size of the grid cells in SCM ABLC is 10 m, which allows for a straightforward comparison with the flight observations since they are over a relatively narrow period in time and space with high temporal resolution (see Table 1) so that vertical features of the clouds are resolved on scales of a few metres. The modelled lower boundary was the ground, but the height of the upper boundary varied with the cloud top height and availability of measurements (see Table 1 for cloud top heights), though the upper boundary was always at least 20 m above the observed cloud top. The time step used was 900 seconds. The total run time was 300 hours, which ensured that model results approach equilibrium for the given boundary conditions. Model results from the last 200 time steps, or 50 hours, were then averaged.

Unsaturated air can be entrained into the cloud at the top and sides of the cloud as well as the bottom and affect microphysical properties in the cloud (e.g. Gerber et al., 2008). Entrained parcels have been found to exist on scales of meters in size, and can reach up to tens of meters into the clouds before mixing homogenizes them with the rest of the cloud (Gerber et al., 2008). In the model, cloud parameterizations do not account for lateral mixing. While our July 8 flight observations are unlikely to have many entrained parcels due to the horizontal extent of the cloud, observations on July 5 and 7 are more likely to contain entrained parcels. Similar to other large-scale atmospheric models, air mixed into the cloud by vertical diffusion at the top and bottom of the cloud is immediately mixed with the cloudy air assuming horizontally uniform thermodynamic cloud properties and ~~cloud droplet number concentration~~CDNC.

*2.2.2 Input profiles and boundary conditions*

Inputs to the SCM-ABLC used aircraft observations of wind speed, relative humidity, LWC, CDNC, and temperature. These inputs provided initial conditions for the model. Additionally, mean vertical profiles of CDNC, temperature, specific humidity, and horizontal winds for each individual aircraft ascent or descent are generated and used to constrain meteorological conditions in the simulation by nudging (see Supplement). Upper boundary conditions for cloud simulations representing the bottom of the free troposphere based on aircraft measurements were nudged as to remain constant over the duration of the model run. The lower boundary conditions at 10 m height for temperature and pressure were specified: the surface temperature was set to 273 K as the flights were all near or over open water and ice edges and the surface pressure was set to 1013 hPa. Between the surface and the altitude of the lowest observation-based initial condition, LWC, horizontal wind, and temperature were calculated based on vertical diffusion with a first order turbulence closure (von Salzen et al., 2013). Model output from the layers beneath the cloud were not considered in the analysis of results in the following sections.

*2.2.3 Boundary Layer Heights*

The choice of model domain vertical extent is important in the SCM-ABLC since processes above the boundary layer are not well represented in the model due to the relatively long time scales and non-local character of free and upper tropospheric processes. For instance, the model does not account for the large-scale transport of air. On the other hand, mixing processes and cloud microphysical processes occur on time scales that are fast compared to large-scale transport of air so that it is sufficient to relax large-scale simulated thermodynamic conditions towards observed profiles. Consequently, we assume that the free troposphere in the model can be represented by the observations at those heights, and properties remain constant over the time period of the profile. ~~TThe boundary layer height was estimated from the height of the base of the observed temperature inversion. The was then variedmodelled boundary layer height was then varied within 30 m of the height of the base of the inversion such that t such that the simulated LWC profile producesproduces a maximum at an altitude similar to the observed profile.~~For each case, the boundary layer height was estimated from the height of the base of the observed temperature inversion. The SCM-ABLC was then run for estimated modelled boundary layer heights within 30 m of that height. The height that resulted in a LWC profile most qualitatively similar to the observed was then used for all subsequent simulations for that case. The model LWC profile was averaged over the final 50 hours of the simulation and then used for all later runs for that case; the procedure was repeated for all cases.

*2.2.5 Autoconversion*

Three autoconversion schemes detailed in the literature were used in the SCM-ABLC: ~~—~~ Wood (2005b), Liu and Daum (2004), and Khairoutdinov and Kogan (2000). The latter two are herein abbreviated as L&D and K&K, respectively. These schemes are described below.

The autoconversion scheme presented by Khairoutdinov and Kogan (2000) separates liquid water in the model into two categories: cloud liquid water and drizzle. It predicts drizzle water and drizzle drop concentration using a prognostic scheme by fitting results from a large-eddy scheme model (Khairoutdinov and Kogan, 2000). This scheme was found to be in good agreement with an explicit model for two cases with no rain and heavy drizzle that were analyzed by Khairoutdinov and Kogan (2000). It was developed for conditions found in the extra-tropics and midlatitudes off the west coasts of continents where stratocumulus cloud layers arise from upwelling of cold water in the ocean (Khairoutdinov and Kogan, 2000). As implemented in the CanAM4, the K&K scheme in the SCM-ABLC has been tuned so that the rate of conversion from cloud droplets to rain drops has been increased relative to the original parameterization (von Salzen et al., 2013). Tuning factors are commonly used in climate models as autoconversion is usually underestimated due to missing processes and other factors (e.g. cloud homogeneity) (Williamson et al., 2015). A tuning factor of 2.5, based on simulations with version 4.3 of the Canadian Atmospheric Model (CanAM4.3), is used in this paper.

The scheme by Liu and Daum (2004) is based on the similar principles as K&K, but does not assume a fixed collection efficiency with respect to droplet radius (Liu and Daum, 2004). The ~~better~~different representation of the ~~physics involved~~autoconversion process in the L&D ~~autoconversion~~ scheme results in stronger dependencies on LWC and ~~cloud droplet number concentration~~CDNC (Liu and Daum, 2004). It also increases the coefficient of variation (the ratio of standard deviation to the mean radius), which affects the threshold radius for autoconversion as broader droplet size distributions tend to have larger autoconversion rates (Liu and Daum, 2004). Unlike K&K, L&D has a threshold radius value before autoconversion begins, preventing rain processes below the threshold. However, this scheme has been shown to overestimate the autoconversion rate above the threshold compared to observation-based estimates for mid-latitude marine clouds (Wood, 2005b).

The Wood (2005b) scheme reduced the empirically-calculated constant term in the L&D parameterization to 12% of its original value based on a comparison with observation-based autoconversion rates in drizzling stratiform clouds that showed lower rates than predicted by L&D. Wood (2005b) also found that the K&K scheme did not over-predict rain as much as the L&D scheme in test cases (flight data described in Wood 2005a), and suggested that the K&K scheme may be useful in situations other than those it was designed for (Wood 2005b). The modified L&D scheme (referred to as the Wood scheme) produced more realistic dependencies of autoconversion on cloud LWC and CDNC compared to the original L&D scheme for drizzle in stratiform clouds (Wood 2005b). All ~~three of these schemes have been used in various modelling applications and~~ were originally developed for the mid-latitudes so~~.~~ ~~A~~as part of our study, we will be evaluating their performance ~~to~~in summer Arctic low clouds.

Three additional cases were simulated in the SCM-ABLC for diagnostic purposes. The first two cases eliminated the impacts of CDNC on the autoconversion rates. This was accomplished by keeping the CDNC constant while retaining the variation in meteorological conditions, such as temperature, relative humidity, and wind speeds. CDNC values of 5/cm$^3$ and 112/cm$^3$, near the extreme observed values, were chosen to represent the range from the observations caused by CDNC. Only the Wood autoconversion scheme was used for these calculations for simplicity. The third case simulated no autoconversion by allowing the variable that represents rain water to be constantly zero, forcing all of the moisture in the clouds to remain in either cloud droplet or vapour form.

*2.2.6 Cloud Profiles*

The cloud vertical extent produced by the SCM-ABLC can differ slightly between different autoconversion schemes, and does in some simulations. However, since the aircraft observations used in our comparisons do not include the entire cloud but only the uppermost part of it, we have focussed on comparing the thicknesses equivalent to the observed portion of the clouds rather than examining the modelled vertical extent. For each observed profile, we used the thickness of cloud measured down from the modelled cloud top to the penetration depth of the aircraft into the cloud during the NETCARE flights. Parts of cloud below the lowest flight level of the aircraft were omitted to avoid only relying on model output.

**2.3. Offline Radiative Transfer Model**

In addition to SCM-ABLC, this study uses an offline version of the radiative transfer model in CanAM4.3. The main attributes of the radiative transfer model are described in von Salzen et al. (2013) and references therein. Only profiles from July 8 are used for the radiative transfer calculations. The flights from July 5 and 7 were not analyzed due to the different solar zenith angles, the different surface albedos, the small number of available cloud profiles, and the possible effects of a different regime at lower CDNC. This resulted in uncertainties that would have made meaningful comparisons difficult. We summarize the ~~most important~~main aspects of the model below.

*2.3.1 Model Description*

Solar and infrared fluxes and heating rates are computed using the Monte Carlo Independent Column Approximation (McICA), which can account for the cloud horizontal variability and vertical overlap (Pincus, Barker, and Morcrette, 2003; Barker et al., 2008). Both the solar and infrared use two-stream solutions, the delta-Eddington approximation for the solar (Zdunkowski et al., 1982), and a perturbation approach for the infrared (Li, 2002).

Absorption by gases is computed using the correlated-*k* method (von Salzen et al., 2013; Lacis and Oinas, 1991). The optical properties of liquid clouds ~~cloud and aerosols~~ are computed using the parameterizations referenced by von Salzen et al. (2013), ~~including .~~separately for solar (Dobbie, Li, and Chýlek, 1999) and infrared (Lindner and Li, 2000) wave numbers. ~~.~~

Aerosols were omitted in the radiative transfer calculations due to their relatively small effects on the radiative fluxes compared to those due to the clouds.

*2.3.2 Cloud Profiles*

The radiative transfer model required profiles of cloud properties including the effective radius, ~~liquid water path (~~LWP~~)~~, cloud fraction, and cloud heights. These profiles were constructed by using model output of cloud properties ~~starting at the top of the simulated cloud down to an altitude that resulted in a cloud thickness equal to the penetration depth of the aircraft into the cloud during the NETCARE flights~~ as described in Section 2.2.6. Clouds below the lowest flight level of the aircraft were again omitted to avoid only relying on model output in all but one of the simulations with the radiative transfer model. We ran a single case using averaged cloud microphysical properties from the observed part of the cloud in order to estimate the difference in radiative fluxes due to the difference in cloud thickness (see Section 3.~~3~~2 for results). The LWC was then multiplied by the grid cell depth and integrated to yield the LWP needed as input to the radiative transfer model. The cloud amount was set to 1 (overcast) at the altitudes where there was cloud, for both the SCM-ABLC and observed profiles. This allowed the optical depths of the modelled and observed clouds to be compared since their thicknesses were equal.

The radiative transfer calculations were performed using the cloud profiles constructed as described above using three configurations: cloud profiles from observations, cloud profiles from the SCM-ABLC, and no clouds. The profile with no clouds was calculated by ~~inputing~~setting zero values for the cloud amount, LWP, and effective radii. The radiative effects of clouds were computed by subtracting the clear-sky radiative fluxes from the radiative fluxes resulting from cloudy profiles.

*2.3.3 Atmospheric State Profiles*

Profiles of pressure, temperature, and water vapour profiles were created using the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)-Interim product by extracting the profiles closest in time and location to the aircraft profiles. The results were vertically interpolated to a vertical grid with 8866 levels spanning from the surface to ~89 km with each layer between 10 and 20 metres thick. The temperature profiles from ERA-Interim were adjusted by a height-independent scaling factor defined by comparing the mean cloud temperatures from the ERA-Interim to the mean observed cloud temperatures, bringing the cloud temperatures closer to the observations. The surface skin temperature was chosen by rounding the temperature interpolation at the lowest level to the nearest degree. Trace gas profiles, including carbon monoxide, carbon dioxide, ozone, nitrous oxide, methane, oxygen, carbon tetrachloride, CFC-11 and CFC-12, were computed by interpolating a climatology from the ECMWF Integrated Forecasting System to all levels.

*2.3.4 Surface Albedo*

The flight on July 8 took place over the open ocean, which we estimated to have a broadband surface albedo of 0.054 based on the solar zenith angle and the time of flight using the parameterization from Taylor et al. (1996). This value is consistent with ocean albedos used by other studies based on measurements (Henderson-Sellers and Huges, 1982; Kukla and Robinson, 1980; Budyko, 1956; Payne, 1972). Albedo values from July 5 and 7 were not used, as the profiles from July 5 and 7 are omitted from the radiative transfer calculations.

## 3. Results and discussion

### 3.1. SCM-ABLC

The green triangles in Figure 2 show the observed mean LWC and CDNC from the profiles listed in Table 1 and Section 2.1.2. As observed by~~expected from~~ Leaitch et al. (2016), the CDNC and LWC are linearly related, despite a slightly different definition of profiles. The variance in our observed relationship is low, with $R^2 = 0.987$ (Table 2, “Observed” case).

To determine whether autoconversion was an important ~~driver~~source of the linear relationship observed between LWC and CDNC by Leaitch et al. (2016), we used the SCM-ABLC to model the LWC for the profiles listed in Table 1 using the three different parameterizations of autoconversion (described in Section 2.2.5). Simulations were conducted with the K&K, L&D, and Wood autoconversion schemes, with two different constant CDNC, and with no autoconversion scheme (see Figure 2 and Table 2 for the cases K&K, L&D, Wood, All CDNC 112/cm$^3$, All CDNC 5/cm$^3$, and No Rain, respectively). Based on these results, we constructed a piece-wise function based on the two linearizations ~~linearizationlinearization~~ of the closest-fitting results to observations, called “L&D and K&K” ~~as it~~ correspondings ~~s~~ to the combination of L&D and K&K schemes, with the K&K scheme ~~so as to use the K&K scheme~~ at CDNC < 20/cm$^3$ and the L&D scheme at higher CDNC.

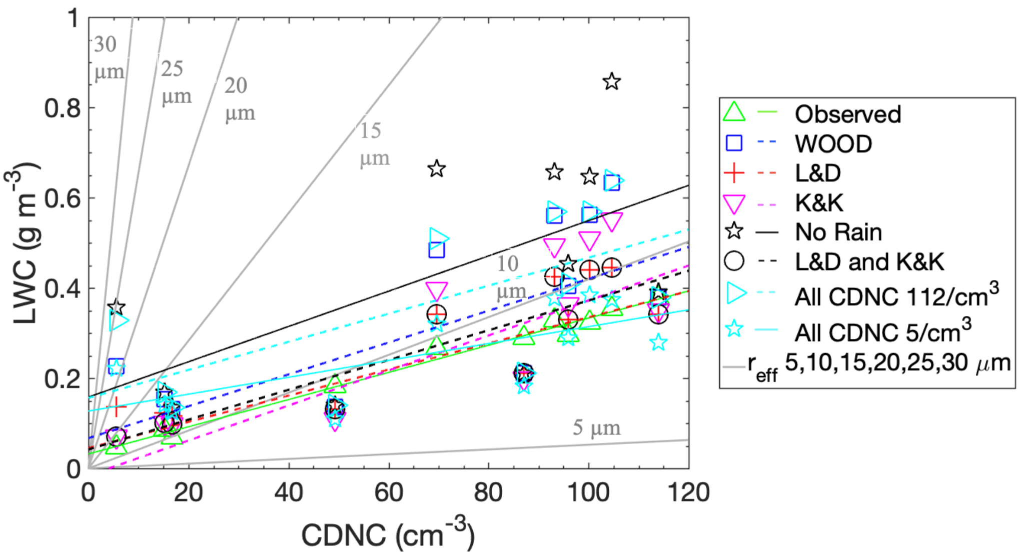


Figure 2. Observed and simulated LWC for three autoconversion schemes in SCM-ABLC, as a function of the observed CDNC specified in the model (symbols). Linear regressions are also shown for the observations and different parameterizations (lines). ‘No rain’ corresponds to the LWC produced by the model with no autoconversion scheme. ‘L&D and K&K’ corresponds to the combination of L&D (>20/cm$^3$) and K&K (<20/cm$^3$) schemes. ‘All CDNC 5/cm$^3$’ and ‘All CDNC

112/cm$^3$' refer to the test cases of the Wood scheme that were run with all of the profiles having constant CDNC of 5/cm$^3$ and 112/cm$^3$, respectively, with the x-axis values corresponding to which original CDNC values they had. The grey lines show the theoretical LWC for varying CDNC given the constant effective radii of the labels.

| | Slope | $R^2$ | Intercept | Mean LWC (g/m$^3$) | ~~Variance~~Variance of LWC | 95% Confidence Interval of Slope (±) |
|---|---|---|---|---|---|---|
| Observed | 0.00301 | 0.987 | 0.032 | 0.24 | ~~0.013~~0.0146 | 0.00026 |
| Wood | 0.00353 | 0.554 | 0.067 | 0.35 | ~~0.032~~0.0357 | 0.00239 |
| L&D | 0.00290 | 0.736 | 0.045 | 0.28 | ~~0.017~~0.0182 | 0.00131 |
| K&K | 0.00388 | 0.707 | -0.016 | 0.29 | ~~0.031~~0.0340 | 0.00189 |
| No Rain | 0.00391 | 0.387 | 0.158 | 0.43 | ~~0.057~~0.0631 | 0.00372 |
| L&D and K&K | 0.00330 | 0.795 | 0.042 | 0.27 | ~~0.020~~0.0218 | 0.00126 |
| All CDNC 5/cm$^3$ | 0.00187 | 0.512 | 0.127 | 0.25 | ~~0.010~~0.0109 | 0.00138 |
| All CDNC 112/cm$^3$ | 0.00311 | 0.443 | 0.156 | 0.37 | ~~0.032~~0.0348 | 0.00263 |

Table 2. Summary of linear fits of observations and model output. See main text for description of cases. Here $R^2$ corresponds to the coefficient of determination, or the proportion of variance in LWC due to CDNC.

Overall, Figure 2 shows that the linearity of the relationship observed between CDNC and LWC can be reproduced by all three autoconversion schemes. Nevertheless, the tested autoconversion schemes tend to overpredict the LWC compared to observations in most cases. The Wood scheme (blue squares) produces the highest variability in LWC and overpredicts the observations the most. The K&K scheme (magenta triangles) has the largest slope but overpredicts the least at lower CDNC, while the L&D scheme (red crosses) has the lowest slope and overpredicts the observations the least at higher CDNC. The slopes and variance in Table 2 show that the L&D scheme is closer to the observations than the Wood scheme in both measures, suggesting that the reduction in autoconversion implemented by Wood to the original L&D autoconversion scheme is not suitable for summer Arctic low clouds. In summary, the simulations with L&D and K&K parameterizations explain most of observed variability in LWC in Fig. 2.

Interestingly, simulations with the simplified parameterizations that do not account for effects of CDNC on autoconversion ('All CDNC 5/cm$^3$' and 'All CDNC 112/cm$^3$') also produce LWC values that are similar to the observed values for ~~each~~some of the flights, ~~ith justw~~but have~~slightly~~ lower $R^2$ values compared to results with L&D and K&K parameterizations (see Table 2). In addition, the relative size of the 95% confidence interval from the 'All CDNC 112/cm$^3$' is large in comparison to the autoconversion cases and the observations (Table 2). This indicates that differences in meteorological conditions, cloud top height, boundary layer depth, and the location of the inversion in the simulations that are associated with different aircraft profiles are partly responsible for the increase in LWC with CDNC according to the linear regression in Figure 2. Due to the lack of droplet sedimentation in the model, the droplets in the 'All CDNC 5/cm$^3$' case are likely to be very large, possibly resulting in more autoconversion than expected and lower LWC values in this simulation. This conclusion is further supported by the results of the simulation which does not include autoconversion and precipitation (the 'No Rain' case). Without autoconversion and precipitation, the simulated LWC is generally much higher than observed, but high values of LWC are still associated with greater ~~high observed~~ CDNC (see Figure 2). The 'No Rain' case has a larger slope and smaller $R^2$ than the other test cases, supporting the hypothesis that autoconversion is an important contributor to the observed linearity between LWC and CDNC compared to the other processes represented by the model. However, the relatively small number of flight profiles substantially affects the robustness of the statistical relationship between CDNC and LWC. Consequently, the model results indicate that a larger number of measurements would be required in order to minimize the impact of meteorological variability on LWC and relationship with CDNC.

Overall, the K&K scheme reproduced the observed LWC better at CDNC below 20/cm$^3$ while the L&D scheme reproduced it better at higher CDNC, suggestive of a regime change like that described by Mauritsen et al. (2011). Below the Mauritsen limit, clouds are CCN-limited and any droplet that forms can drizzle out. This process seems to be better represented by the K&K scheme which continuously converts cloud droplets to rain drops with no threshold for conversion, compared to the other schemes which have a constant threshold, i.e the L&D and Wood schemes. At higher CDNC, the

K&K scheme overpredicts the LWC compared to the L&D scheme. To capture this change in regime, we combined the L&D and K&K schemes by using the K&K scheme to model the three profiles with CDNC below 20/cm$^3$ and the L&D scheme for the rest. This combination performed the best at obtaining the lowest variance and the overall slope is similar to the observations (Table 2, "L&D and K&K" case). The exact cut off for the tenuous cloud regime is ~~debatable~~likely dependent on the environment. In the original observations of Mauritsen et al. (2011), they discussed a threshold of 10/cm$^3$. However, both Mauritsen et al. (2011) and Leaitch et al. (2016) suggested that this limit is more reflective of a change in regime than a specific numerical cutoff and that the actual threshold depends on location and time. The three lowest mean CDNC values used in our modelling were all less than or equal to 17/cm$^3$, similar to the limit suggested by Leaitch et al. (2016) of 16/cm$^3$. We stress, however, that our data set is limited to only three profiles with CDNC in the tenuous cloud regime and further work would be needed before these results could be generalized. Nevertheless, our findings are consistent with the observational results from Mauritsen et al. (2011) and Leaitch et al. (2016), and further demonstrate the possible importance of this regime change at low CDNC. Other models may also need to consider this regime change to better represent Arctic low clouds.

The two observed profiles for which the model consistently underpredicted the LWC (at CDNC concentrations of 49/cm$^3$ and 87/cm$^3$) had lower wind speeds in the cloud and less of a difference in wind speeds between in-cloud and above the cloud than some of the other profiles. This may have prevented sufficient water vapour from mixing into the cloud, thereby preventing conversion of cloud water vapour to liquid water.

Other studies have previously noted that autoconversion schemes often do not represent the rain rates in the Arctic very well (Croft et al., 2016; Zhang et al., 2002; Olsson et al., 1998). Olsson et al. (1998) speculated that the discrepancy between modelled and observed rain rates may be due to the size of droplets, as small droplets can fail to initialize autoconversion when the threshold is too large. Our results support this theory at low CDNC: the K&K scheme, which has no threshold for autoconversion, performs the best at low CDNC, suggesting that the thresholds for autoconversion may be too high in the L&D and Wood schemes at these droplet concentrations, resulting in overpredicted LWC. We found that the L&D scheme does best at higher CDNC, so there may be a regime change between low and high CDNC. Although the model comparisons carried out by Stevens et al. (2018) did not directly compare autoconversion schemes, they demonstrated that both large-eddy simulation and numerical weather prediction models showed pronounced tendencies to increase LWP with increasing CDNC, and that LWP is highly sensitive to CDNC, consistent with our results.

Although the L&D scheme best reproduces the nearly linear relationship between the observed LWC and CDNC, the linearity appears to be well-reproduced by all three of the autoconversion schemes that we examined. This indicates that autoconversion is indeed an important driver of the linearity between LWC and CDNC in this instance, ~~as~~since the no-autoconversion case ~~with no autoconversion~~ is much less linear and with lower $R^2$ (see Figure 2 and Table 2). Since the linear fit for the ‘No Rain’ case explains less of the variability than the linear fits for the simulations with autoconversion parameterizations, we surmise that autoconversion is a driver of the linear relationship. As such, autoconversion appears to be sufficient to drive the linearity observed between LWC and CDNC by Leaitch et al. (2016), based on our modelling. This is consistent with the second aerosol indirect effect, and similar to the findings by Stevens et al. (2018). ~~However, relationships between CDNC and LWC were previously analyzed and explained in other studies, including Gerber et al. (2008), Albrecht (1989), and Jensen et al. (1985). From these studies, it is clear that there may be strong correlations between CDNC and LWC due to effects of turbulent mixing and evaporation of cloud droplets, depending on the efficiency of mixing versus evaporation. However, t~~There is no evidence of strong turbulent mixing in the observations. Further, we are assuming that turbulence affects the LWC but not the CDNC in the simulations~~.~~ since ~~W~~we ~~also~~ do not account for cloud inhomogeneities. As such, the simulated relationship between LWC and CDNC may be incomplete. Future ~~generations of modellers~~work may have to ~~think about how to~~ better incorporate subgrid-scale cloud mixing processes in models.

### 3.~~3~~2. Radiati~~on~~ve fluxes

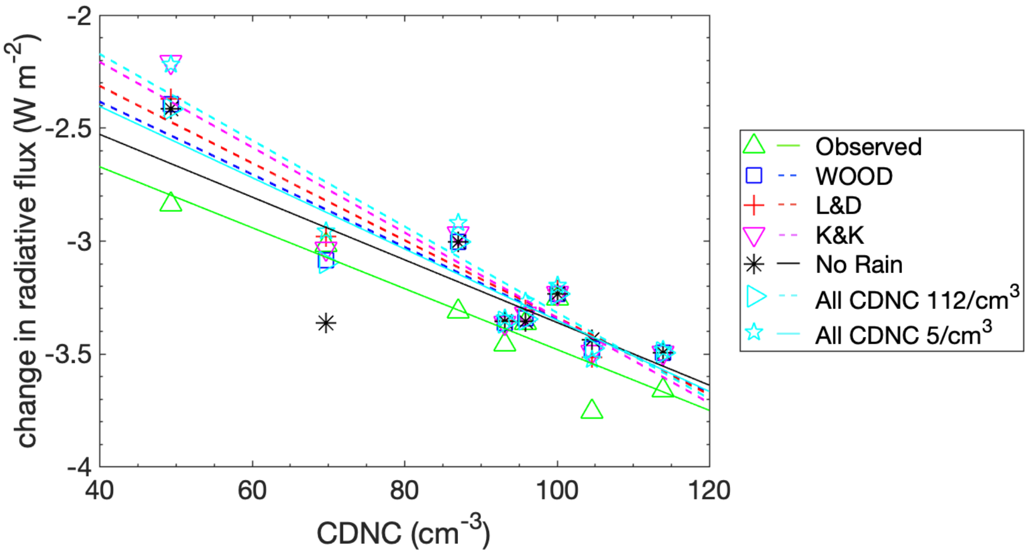


Figure 3. Change in upward longwave radiation at the top of the atmosphere due to the presence of cloud, on July 8 only, wherein the input cloud variables were from the SCM-ABLC output or based on observations. The radiative flux for the 'observed' case is calculated using the radiative transfer model with observed cloud ~~inputs from observations~~properties.

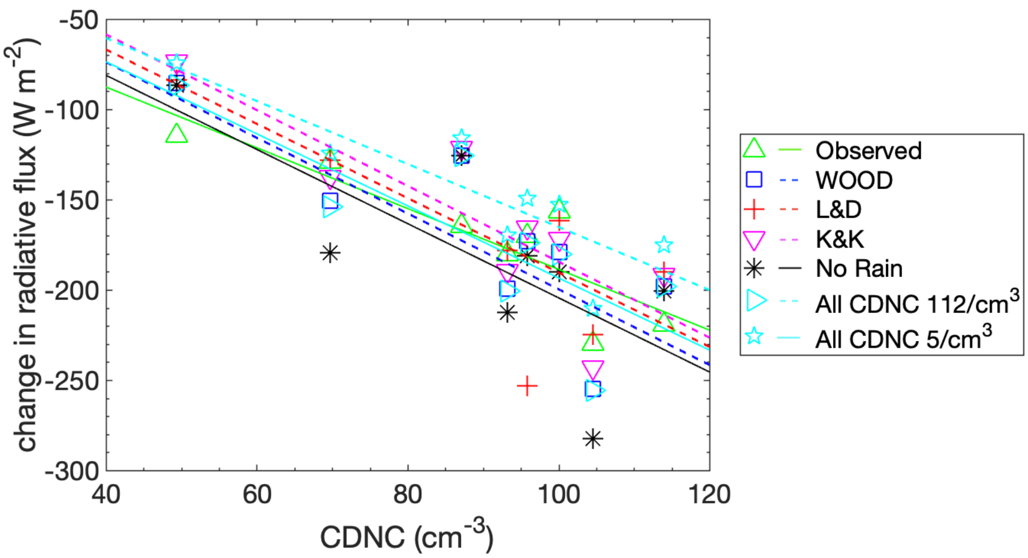


Figure 4. Change in downward shortwave radiation at the surface due to the presence of cloud, wherein the input cloud variables were from the SCM-ABLC output or based on observations. The radiative

flux for the ‘observed’ case is calculated using the radiative transfer model with observed cloud properties.

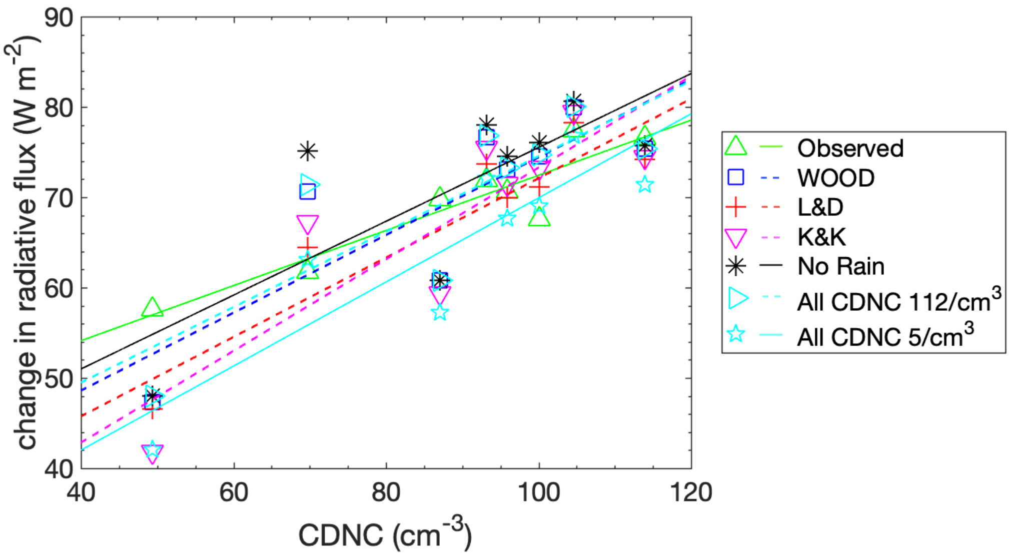


Figure 5. Change in downward longwave radiation at the surface due to the presence of cloud, wherein the input cloud variables were from the SCM-ABLC output or based on observations. The radiative flux for the ‘observed’ case is calculated using the radiative transfer model with observed cloud properties.

The offline radiative transfer model was run using simulated profiles of liquid water path and effective radius from the SCM-ABLC as input for the flights on July 8, as well as with the clouds removed, to compute the cloud radiative effect (CRE). For these calculations, all profiles were assumed to be over open ocean. The green triangles in Figure 3 are the longwave ~~radiative fluxes~~CRE at the top of the atmosphere calculated from the observed liquid water path and effective radius, while the other symbols represent the longwave ~~radiative flux~~CRE calculated from the model output using the different autoconversion schemes in the SCM-ABLC. Since the effective radii are roughly constant over all of the cases that were considered and the LWC was found to linearly increase with the CDNC, the optical depth, and therefore the extinction, estimated from the plane-parallel approximation, also varies linearly at these relatively low CDNC (see Table 3). This results in the longwave ~~radiative flux~~CRE at the top of the atmosphere linearly decreasing with increasing CDNC. We find that slopes are slightly larger for the simulations than for observations, with the exception of the “No Rain” case (see Table 3). The $R^2$ value indicates that the relationships are linear to a very good approximation for each case, but lowest for the "No Rain" case (see Table 3). Further, using a t-test, the longwave calculations showed no significant difference at p=0.05 in the ~~radiative effect due to the cloud~~CRE between the different autoconversion schemes (see Table 4). However, there is a significant difference between the ~~radiative calculations due to the clouds~~CRE modelled and those based on observations at p=0.05 due to the differences in modelled and observed effective radii and LWC for all autoconversion schemes except for the "No Rain" case where no autoconversion was included (see Table 4).

| | | Slope | Intercept | $R^2$ | 95% Confidence Interval of Slope (±) |
|---|---|---|---|---|---|
| Upward longwave flux at the top of the atmosphere | Observed | -0.0135 | -2.1317 | 0.832 | 0.0061 |
| | Wood | -0.0161 | -1.7391 | 0.857 | 0.0066 |
| | L&D | -0.0171 | -1.6294 | 0.898 | 0.0058 |
| | K&K | -0.0189 | -1.4509 | 0.861 | 0.0076 |
| | No Rain | -0.0139 | -1.9720 | 0.658 | 0.0100 |
| | All CDNC 5/$cm^3$ | -0.0158 | -1.7719 | 0.853 | 0.0071 |
| | All CDNC 112/$cm^3$ | -0.0191 | -1.4080 | 0.877 | 0.0065 |
| Downward shortwave flux at the surface | Observed | -1.6829 | -20.3366 | 0.770 | 0.9196 |
| | Wood | -2.0970 | 10.0677 | 0.668 | 1.4270 |
| | L&D | -2.0583 | 15.4632 | 0.590 | 1.7152 |
| | K&K | -2.1001 | 25.5905 | 0.721 | 1.3036 |
| | No Rain | -2.0547 | 1.06990 | 0.537 | 1.9075 |
| | All CDNC 5/$cm^3$ | -1.9961 | 6.2135 | 0.654 | 0.9906 |
| | All CDNC 112/$cm^3$ | -1.7445 | 9.2692 | 0.756 | 1.4515 |
| Downward longwave flux at the | Observed | 0.30527 | 41.90649 | 0.865 | 0.1207 |
| | Wood | 0.43052 | 31.38566 | 0.696 | 0.2844 |
| | L&D | 0.43937 | 28.17262 | 0.818 | 0.2072 |

| | | | | | |
|---|---|---|---|---|---|
| surface | K&K | 0.50730 | 22.55339 | 0.751 | 0.2921 |
| | No Rain | 0.40879 | 34.63778 | 0.590 | 0.3403 |
| | All CDNC 5/cm$^3$ | 0.46542 | 23.38898 | 0.772 | 0.2527 |
| | All CDNC 112/cm$^3$ | 0.41759 | 32.78588 | 0.674 | 0.2900 |

Table 3. Summary of linear fits of radiation model ~~output~~CRE. See main text for description of cases. ~~Here $R^2$ corresponds to the coefficient of determination, or the proportion of variance in the change in radiation due to the presence of cloud due to CDNC.~~

| | | L&D | K&K | 5/cm$^3$ | 112/cm$^3$ | No Rain | Observed |
|---|---|---|---|---|---|---|---|
| Upward longwave flux at the top of the atmosphere | WOOD | 0.237 | 0.169 | 0.047 | 0.147 | 0.378 | 0.036 |
| | L&D | - | 0.500 | 0.060 | 0.196 | 0.323 | 0.013 |
| | K&K | - | - | 0.091 | 0.165 | 0.180 | 0.038 |
| | All CDNC 5/cm$^3$ | - | - | - | 0.050 | 0.120 | 0.016 |
| | All CDNC 112/cm$^3$ | - | - | - | - | 0.423 | 0.038 |
| | No Rain | - | - | - | - | - | 0.184 |
| Downward shortwave flux at the surface | WOOD | 0.006 | 7.79E-5 | 4.11E-4 | 0.027 | 0.023 | 0.976 |
| | L&D | - | 0.137 | 8.90E-5 | 0.005 | 0.011 | 0.045 |
| | K&K | - | - | 0.003 | 1.89E-4 | 0.004 | 0.352 |
| | All CDNC 5/cm$^3$ | - | - | - | 3.50E-4 | 0.002 | 0.007 |
| | All CDNC 112/cm$^3$ | - | - | - | - | 0.027 | 0.886 |
| | No Rain | - | - | - | - | - | 0.386 |
| Downward longwave flux at the surface | WOOD | 0.010 | 0.012 | 2.24E-5 | 0.061 | 0.034 | 0.800 |
| | L&D | - | 0.629 | 4.32E-4 | 0.009 | 0.015 | 0.389 |
| | K&K | - | - | 8.66E-4 | 0.014 | 0.007 | 0.648 |
| | All CDNC 5/cm$^3$ | - | - | - | 5.11E-5 | 3.55E-4 | 0.108 |
| | All CDNC 112/cm$^3$ | - | - | - | - | 0.041 | 0.729 |
| | No Rain | - | - | - | - | - | 0.513 |

Table 4. t-test results for the change in ~~radiative flux~~CRE ~~due to the presence of cloud~~ for July 8.

A similar decreasing linear relationship exists for the downward shortwave CRE at the surface (Figure 4). However, there is no significant difference at p=0.0~~1~~5 (see Table 4) in the downward shortwave CRE at the surface between each scheme and the observation-based ~~model runs~~radiative transfer calculations on July 8 except for the "L&D" and "All CDNC 5/cm$^3$" cases.

~~A similar decreasing linear relationship exists for the downward shortwave radiation at the surface (Figure 4). However, there is no significant difference at p=0.01 (see Table 4) in the downward shortwave radiative effect at the surface between each scheme and the observation-based model runs on July 8 except for the "All CDNC 5/cm$^3$" case.~~

An increasing linear relationship exists for the downward longwave ~~radiation~~CRE at the surface (Figure 5), indicating that clouds with higher CDNC result in greater longwave radiative fluxes when compared to the case with no cloud. The calculation based on observations results in the highest $R^2$ value (see Table 3), implying that autoconversion schemes do not replicate this result quite as well, although the L&D scheme does quite well at linearizing despite having a very different slope and intercept (Table 3). T-tests show, however, that none of the autoconversion schemes result in downward longwave radiation values that differ significantly (p=0.0~~1~~5~~01~~) from observation-based calculations, though the "All CDNC 5/cm$^3$" case and the "No Rain" case differ significantly (p=0.05) from all other autoconversion-based cases (Table 4).

From these comparisons of the July 8 data, the most important result is that there is an offset in the ~~radiative calculations~~CRE based on the observations versus the SCM-ABLC model output for the upward longwave ~~radiative flux~~CRE at the top of the atmosphere which is significant at p=0.05 for all cases but "No Rain," which had no autoconversion processes. However, the downward shortwave ~~radiative flux~~CRE at the model surface shows that all autoconversion schemes but "All CDNC 5/cm$^3$" and "L&D" produce ~~fluxes~~CRE that are not significantly different (p=0.0~~1~~5~~01~~) from those calculated based on observed cloud profiles. A final takeaway from the t-tests was that the Wood autoconversion produced small but statistically significantly different downward shortwave ~~radiation~~CRE at the surface from the other two autoconversion schemes from the literature at a significance of p=0.0~~1~~5~~01~~, while the L&D and K&K schemes did not significantly differ from each other. This may require further investigation as the L&D and Wood schemes differ only by a constant, while the K&K scheme ~~differs significantly~~uses an additional variable as well as different constants ~~from~~than~~differs significantly from~~

those two. In addition to this, the "No Rain" case with no autoconversion processes differed significantly at p=0.05 from all other SCM-ABLC-based input to the downward shortwave ~~flux~~CRE at the surface, so the presence of an autoconversion scheme in the cloud model produces a significant change in the result~~ings of radiative modelling.~~ CRE.

A sample calculation was carried out to test the radiative effects of extending the cloud to the surface, as was surmised to occur by observers during the July 8 flight. The extension of the cloud was assumed to have a LWP and effective radii equal to the average of those values in the observed portion of the cloud. This resulted in a decrease of less than 1% in the longwave ~~radiative flux~~CRE at the top of the atmosphere. Similarly, the change in the downward longwave ~~flux~~CRE at the surface was also small, with the newly modelled cloud increasing the ~~radiative flux~~CRE by almost 4%. The results were most sensitive in the downward shortwave ~~flux~~CRE at the surface, with the thicker cloud decreasing the original ~~flux~~CRE by approximately 35%. The small changes in the longwave ~~radiation~~CRE indicate that the temperatures of the ground and the cloud top are similar. The larger change in the downward shortwave ~~flux~~CRE at the surface indicates that the observed portion of the cloud is insufficiently thick to estimate the effect on the shortwave ~~flux~~CRE on its own.

Overall the results from Table 3 show that the model-based ~~radiative flux~~CREs ~~calculations~~ produce more negative slopes than those based on observations, suggesting that the model overestimates the relationship between CDNC and shortwave ~~radiative flux~~CRE, and that the first aerosol indirect effect may be overestimated by the three autoconversion parameterizations ~~examined from the literature~~used in this study. The first aerosol indirect effect depends on a realistic sensitivity of fluxes to changes in CDNC in response to changes in CCN concentrations. However, the best agreement in slopes for the change in shortwave ~~radiative flux~~CRE is found in the simulations which assume a constant CDNC in parameterizations of autoconversion (see Table 3). In particular, the change in shortwave ~~flux~~CRE is much greater for the K&K parameterization than calculation based on observations, which is consistent with the particularly strong non-linear dependency of this parameterization on CDNC~~, indicating that aerosol indirect effects may be especially overestimated with this parameterization~~.

## 4. Conclusion

Our model simulations show that the linear relationship between LWC and CDNC observed by Leaitch et al. (2016) in summer Arctic low clouds is consistent with parameterizations of autoconversion, although other processes, such as variability in meteorological conditions, entrainment of dry air without mixing and increased condensation rates, may contribute to the observed relationship. The choice of autoconversion scheme in the SCM-ABLC changes the simulated relationships between LWC and CDNC, with the best simulated linear relationship (highest $R^2$) obtained from a combination of the K&K scheme at CDNC below 20/cm$^3$ and the L&D scheme at higher concentrations. These results are consistent with a regime change between very low and higher CDNC corresponding to the Mauritsen limit. Below this limit, droplet concentrations are CCN-limited and droplets are expected to grow and fall out quickly, consistent with the constantly-drizzling K&K scheme. In contrast, the L&D and Wood schemes have threshold radii before drizzle occurs, consistent with our understanding of drizzle formation in regions ~~of the world where~~with greater CDNC~~ are higher~~. Due to a lack of observational data, the exact transition above which the L&D scheme performed better could only be constrained to a range of 17-48/cm$^3$. It is important to note that our observations below the Maurtisen limit only consisted of 3 profiles and that our conclusions are ~~highly~~ dependent on this limited data set. It would be of interest to examine whether this regime change can be reproduced with more data, in other parts of the summer Arctic, and with other models. ~~It would be of interest to examine whether a regime change can be reproduced with more data and in other models, as t~~The observational data examined in this study have shown that cloud properties, such as effective radius, vary somewhat between the regimes, with an average observed effective radius of 12 µm below the Mauritsen limit versus 10 µm above it, which may also be interesting to reexamine with a larger dataset. The choice of autoconversion scheme is most relevant when examining the cloud microphysical properties for their own sake, as opposed to radiation, and the combination of K&K and L&D schemes should be used for these conditions.

The ~~radiative impacts of the~~ modelled downward shortwave and longwave ~~radiation~~cloud radiative effects at the surface mostly did not differ significantly at p=0.0~~1~~5~~01~~ from those due to the observations using ~~all~~the~~all~~ three autoconversion schemes from the literature except for the L&D scheme which had p=0.045 for the downward shortwave CRE. The ~~radiative impacts of the~~ modelled upward longwave ~~radiation~~CRE at the surface did differ significantly from those due to the observations for these schemes at~~ p=0.05~~. This suggests that the microphysical parameters such as LWP and effective radius simulated by all the autoconversion schemes were sufficiently similar to observations for shortwave calculations but not for upward longwave calculations. The Wood autoconversion scheme simulated downward shortwave radiation at the surface that was significantly different ~~(p=0.101)~~ from the K&K and L&D schemes, although not from the observations. This appears to be due to the higher modelled LWC in the Wood scheme, and indicates that this scheme may be less suitable for modelling low clouds in the summer Arctic, which tend to have low LWC.

Future work should determine the prevalence of a linear relationship between LWC and CDNC in other clouds, and whether autoconversion, therefore the second aerosol indirect effect, is one of its primary drivers. Since part of our results were highly dependent on CDNC below the Mauritsen limit, determining the prevalence of clouds in a CCN-limited regime is needed to understand the importance of implementing different autoconversion schemes in clouds. There remain large uncertainties in the radiative effect of low clouds in the summer Arctic, and ensuring that cloud microphysical properties are properly represented in models is one way to begin to reduce that uncertainty. Another important component of reducing the uncertainty in the radiative effect of clouds like these in the summer Arctic involves comparing the calculated radiative effect to observations. Remote sensing or in-situ observations would allow us to improve our understanding of modelled cloud radiative effects. These results could be relevant for other regions with low CDNC such as clean marine clouds and fogs. It may also be of interest to compare these findings to a large-eddy simulation model. Another interesting future direction would be to probe our assumption that the cloud is in equilibrium. This could be accomplished by changing the CDNC abruptly after the model spin-up to observe the transient behaviour of the model microphysics, as performed by Gettelman (2015).

*Author contributions*

JD and RYWC wrote this paper. RYWC, KVS, and IF provided project direction and supervision. RYWC and IF provided funding. KVS and JC provided the majority of the methodology and software. WRL and GL also contributed methodology. Investigation was primarily carried out by JD, with input from RM. All authors were involved in the review of this paper.

*Acknowledgements*

We thank the Canadian Centre for Climate Modelling and Analysis (CCCma) for computing time on their server for running the SCM-ABLC and radiative transfer model. Funding for this work was provided by the Marine Environmental Observation, Prediction and Response Network (MEOPAR), which is a federally-funded Networks of Centres of Excellence (NCE) and the Natural Sciences and Engineering Research Council of Canada (NSERC) through Discovery Grants and the NETCARE project of the Climate Change and Atmospheric Research Program. NETCARE was also funded by additional financial and in-kind support from the Alfred Wegener Institute, and Environment and Climate Change Canada, Fisheries and Oceans Canada, and the Major Research Project Management Fund at the University of Toronto.

We acknowledge the use of imagery from the NASA Worldview application (https://worldview.earthdata.nasa.gov/) operated by the NASA/Goddard Space Flight Center Earth Science Data and Information System (ESDIS) project.

*Competing interests*

The authors declare that they have no conflict of interest.

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