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Microphysical processes involving the vapour phase dominate in simulated low-level Arctic clouds

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Abstract. Current general circulation models struggle to capture the phase-partitioning of clouds accurately, either overestimating or underestimating the supercooled liquid substantially. This impacts the radiative properties of clouds. Therefore, it is of interest to understand which processes determine the phase-partitioning. In this study, microphysical process rates are analyzed to study what role each phase-changing process plays in low-level Arctic clouds. Several months of cloud-resolving ICON simulations using a two-moment cloud microphysics scheme, are evaluated. The microphysical process rates are extracted using a diagnostic tool introduced here, which runs only the microphysical parameterisation using previously simulated days. It was found that the importance of a process varies for the polar night and polar day, although phase changes that involve the vapour phase dominate. Additionally, the dependence of each process on the temperature, vertical wind and saturation was evaluated. Going a step further, we used the combined evaporation and deposition rates to demonstrate the Wegener-Bergeron-Findeisen process occurrence. This study helps to better understand how microphysical processes act in different regimes. It additionally shows which processes play an important role and contribute to the phase-partitioning in low-level Arctic clouds. Therefore, these processes can be better targeted for improvements in the model that aim to better represent the phase-partitioning of Arctic low-level mixed-phase clouds.

1 Introduction

Several studies (Ebell et al., 2020; Shupe and Intrieri, 2004; Curry and Ebert, 1992) showed the importance of clouds for the Arctic radiative budget. Clouds further play a role in different feedback mechanisms, for instance, the cloud-phase feedback (Mitchell et al., 1989), and either amplify (positive feedback) or dampen (negative feedback) the warming. As the Arctic is warming up to four times faster than the global average (Rantanen et al., 2022), it is of interest to which extent clouds play a role. Currently, the question still remains though whether the total cloud feedback is positive or negative (Middlemas et al., 2020; Goosse et al., 2018). A specific challenge is the cloud-phase feedback as the changes in the cloud's phase-partitioning impact the cloud radiative effect (Mitchell et al., 1989; Storelvmo et al., 2015). The reason for these uncertainties regarding the cloud feedbacks stems from the difficulties of models on all scales to represent clouds, especially mixed-phase clouds (MPCs) accurately (Kay et al., 2016; Zelinka et al., 2020). These difficulties are connected to the complexity of microphysical processes in clouds and their parameterisations in models. One consequence is that many models are unable to capture the

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phase-partitioning in clouds correctly (Tan et al., 2016). As a result, it is hard to quantify cloud feedbacks causing uncertainties in the climate projections (Zelinka et al., 2020).

Some models struggle to represent supercooled liquid in MPCs and often underestimate it (Cesana and Chepfer, 2012; Kiszler et al., 2023). Huang et al. (2021) link this underestimation of cloud liquid in the CESM1 model to the Wegener-Bergeron-Findeisen (WBF) process, where ice grows at the expense of liquid water due to the lower saturation required above frozen surfaces. While sometimes the limited spatial and temporal resolution can cause the full glaciation of a cloud (Storelvmo and Tan, 2015), other studies showed the importance of the WBF process to estimate the climate forcing of MPC correctly (Shaw et al., 2022; McGraw et al., 2023). In contrast, Zhang et al. (2020) found an overestimation of liquid in the E3SM model after several changes, including a switch in the ice nucleation scheme (new: Classical Nucleation Theory, Wang et al., 2014) and microphysical parameterisation scheme (new: Gettelman and Morrison, 2015). Again, this shows that the phase-partitioning and representation of cloud microphysical processes remains a challenge (Korolev et al., 2017; Morrison et al., 2020).

To understand where these uncertainties come from and address them, many studies have used sensitivity tests by varying process parameters or aerosol concentrations, where the subsequent changes of the cloud macro- and microphysics and other model components are evaluated (e.g. Lasher-Trapp et al., 2018; Shaw et al., 2022). This can provide valuable insights but makes it hard to untangle the exact contribution of each process. Additionally, the number of feasible model runs cannot cover the full range of possible parameter changes and combinations. Another approach aims to evaluate the microphysical process rates directly. This was done, for instance, by Gettelman et al. (2013) for a general circulation model (GCM) to look at the relative importance of microphysical processes in climate models using daily rates. In a recent paper, Barrett and Hoose (2023) used so-called microphysical pathways, which include different sets of microphysical processes, to study an idealized deep convective system. Kalesse et al. (2016) found a strong connection between the deposition rate of snow and the snow mass mixing ratio in a case study of an Arctic low-level cloud. Fan et al. (2017) studied the effect of changing ice nucleating particles (INP) and cloud condensation nuclei (CCN) concentrations on process rates, finding an increase in condensation, evaporation, deposition, sublimation and riming with increasing aerosols.

This study uses microphysical process rates to determine which processes contribute most to phase changes in Arctic low-level clouds (LLC). The focus lies on Svalbard, where LLCs frequently occur (Gierens et al., 2020; Nomokonova et al., 2019). Svalbard has an above average occurrence of MPCs (45-60 %) in comparison to the rest of the Arctic (30-50 %, Mioche et al., 2015) making the location ideal for studying the phase-partitioning of clouds. Cloud-resolving simulations with ICON-LEM are used to explore the importance of the microphysical processes for the phase-partitioning. To achieve this, a diagnostic tool is introduced, which provides the process rates using the simulation output as input. Several aspects are taken into account in the evaluation, those are the difference between polar night and day, temperature, vertical wind and saturation regimes. Additionally, we use the deposition and evaporation rates to evaluate if and how the WBF process impacts the amount of liquid and frozen hydrometeors in the simulated clouds.

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2 Methods and data

2.1 Model simulations and data selection

The ICON-LEM (Dipankar et al., 2015; Heinze et al., 2017) simulations which we performed cover a circular domain with approx. 100 km diameter centred in Ny-Ålesund (Svalbard, lon-lat) and run with approx. 600 m resolution. The general setup follows the papers by Kiszler et al. (2023) and Schemann and Ebell (2020) with each simulation covering 24 h, although the first 3 hours are excluded in the analysis to avoid the spin-up. The forcing is from a 2.4 km ICON-NWP simulation, which is run on a larger domain and forced by the German weather service global ICON-NWP runs. The turbulence is parameterised by a 3D-Smagorinsky scheme (Dipankar et al., 2015). The two-moment scheme from Seifert and Beheng (2006) with an added hail class Blahak (2008) is used for the microphysics (referred to as SB). A slight adaptation was made to the default ICON microphysical settings. We use the Segal and Khain (2006) cloud condensation nuclei (CCN) activation with maritime aerosols, as well as the heterogeneous ice nucleation from Phillips et al. (2008) with the maritime aerosol concentrations. The output is given in the form of the vertical column above the grid cell containing Ny-Ålesund (meteogram) for every 9 s on 150 levels. This output includes the following hydrometeor mass mixing ratios and number concentrations: cloud droplets, rain, ice, snow, graupel and hail.

For the analysis, a subset of the data, which only includes low-level clouds, was created. This was done by first selecting all grid boxes which are cloudy using a threshold for the hydrometeor concentration of 10^{-8} kg kg^{-1} (same as in Kiszler et al., 2023; Schemann and Ebell, 2020) above which a grid box is defined as cloudy. For a cloud to be classified as low-level, the cloud top height must be below 2.5 km (same as Gierens et al., 2020; Chellini et al., 2022). Additionally, precipitating hydrometeors are not differentiated from non-precipitating ones. Therefore, a cloud with rain, graupel, hail or snow that reaches the ground will have a cloud base height at the ground. Further, if there is a cloud with a cloud top height higher than 2.5 km above the low cloud, we only use these cases if the higher cloud's bottom height is at least 500 m higher than the low cloud's top height. The frozen and liquid hydrometeors are grouped in the analysis to focus on phase transitions. The frozen mass mixing ratios ("frozen mass", kg kg^{-1}) is the sum of cloud ice, graupel, hail, and snow, and the liquid mass mixing ratios ("liquid mass", kg kg^{-1}) is the sum of cloud droplets and rain. The occurrence of low-level clouds and their composition varies between seasons (Mioche et al., 2015). Therefore, two sets of data are used. One covers the polar night (November 2021 - February 2022) and one the polar day (May-August 2021). In total, for the polar night, there are around 26.3 days' worth of low-level clouds, and for the polar day, there are around 37.9 days.

2.2 Microphysics parameterisation wrapper

To extract the process rates, this study uses a "microphysical parameterisation wrapper". The goal is to provide a simple diagnostic tool with spatial and temporal flexibility. Therefore, we chose to run the two-moment SB scheme and the saturation adjustment (for condensation/evaporation) independently from the model. A meteogram (single column) or 3D output file from

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a previous simulation can be used as input for the wrapper. The model output is provided as input to the microphysical scheme in each timestep. It computes a single timestep, writes out the rates and continues with the following timestep. This approach allows the use of previous simulations from which the meteogram or 3D output of the required variables exists.

This approach has the clear advantage of being very fast compared to rerunning a full simulation, and one can focus on single processes. Further, outputting an entire domain of microphysical process rates is extremely space-consuming in most cases and can be avoided by just using a spatial and/or temporal selection. Another advantage is that the values of the thermodynamic variables (temperature T, pressure p, vertical velocity w, density ρ) are known exactly when they are used to compute the processes. This is not the case if one runs the entire model and outputs the thermodynamic variables only after additional physics and dynamical schemes have run. Additionally, it is possible to explore potential sensitivities of microphysical processes by applying changes inside of the wrapper and using it as a test suite. As this tool is simplified and only captures a part of the model, the advantages come with some limitations. One must keep in mind that any transportation (advection and precipitation) of hydrometeors cannot be included as the model itself is not run. In this study, we are only interested in the microphysical processes. Therefore, this is not an issue.

The mass change due to a process is computed by taking the difference between the mass before and after the process and is called (ΔQ_{proc}). Here, a timestep (Δt) of 3 seconds is used for the time integration. Therefore, the process rate ($\frac{\Delta Q_{proc}}{\Delta t}$) is given as the hydrometeor mass mixing ratio change over 3 seconds and is denoted as the "tendency" (kg kg^{-1} 3s^{-1}) in the following sections. As mentioned before, the hydrometeors are summed up into a liquid and frozen mass. The same is done with the processes, meaning, for example, that deposition is the sum of deposition onto ice particles, snow, graupel and hail. In this study, only processes that cause phase changes are included, as we are interested in processes that contribute to the phase-partitioning. E.g. frozen collisions are not evaluated as all frozen hydrometeors are summed up to a single class and compensate each other. Many of the processes evaluated in this study have self-explanatory names. Nevertheless, a brief process summary is given here and in Table 1 to prevent misunderstandings.

Deposition and Sublimation includes either the decrease or increase of water vapour due to phase changes from frozen to vapour. They are computed by the same process and split into negative (sublimation) and positive (deposition) contributions to the frozen mass.

Homogeneous and heterogeneous ice nucleation describes as one part the homogeneous nucleation of liquid aerosols, although it is rarely cold enough (T<30 °C) in the clouds used in this study to happen. The heterogeneous nucleation describes nucleation via immersion freezing and deposition nucleation. The parameterisation follows as mentioned Phillips et al. (2008). As homogeneous cloud droplet freezing did not occur for the low-level clouds, it is neglected here.

CCN activation describes the activation of cloud condensation nuclei following the parameterisation of Segal and Khain (2006).

Frozen evaporation and Melting refer to the melting of frozen hydrometeors, which can entail evaporation, but both are treated separately, leading to a process called "evaporation" also for the frozen hydrometeors.

Riming describes the accumulation of liquid mass on a frozen hydrometeor by decreasing the liquid mass and increasing the

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Process	ΔQ_L	ΔQ_F	ΔQ_v
Ice nucleation	-	+	-
CCN activation	+	/	-
Deposition	/	+	-
Sublimation	/	-	+
Evaporation	-	/	+
Condensation	+	/	-
Riming	-	+	/
Rain freezing	-	+	/
Melting	+	-	/

Table 1. Impact of each process on the hydrometeor masses for liquid (ΔQ_L) and frozen (ΔQ_F) as well as the water vapour (ΔQ_v). The liquid class contains cloud droplets and raindrops, the frozen class contains ice particles, snow, graupel, and hail. A plus indicates an increase in the hydrometeor mass, and a minus a decrease.

frozen mass. In SB in ICON, this also includes the Hallet-Mossop secondary ice production, and if T>0 °C enhanced melting after riming will take place, making the frozen mass increase due to riming smaller.

Condensation and Evaporation includes either the decrease or increase of water vapour due to phase changes from cloud droplets and raindrops to vapour. They are the positive (condensation) and negative (evaporation) contributions of the saturation adjustment to the liquid mass.

Rain freezing only includes the freezing of raindrops and not cloud droplets. As both are summed up, though, this causes a decrease of the total liquid mass while the total frozen mass increases.

3 Results

3.1 Dominating processes in low-level clouds

We used a simple but straightforward approach to understand which processes dominate the phase-partitioning in low-level clouds. For each process, the mean value over all cases was computed. The mean values can vary, for instance, with temperature, as shown in the next section, so the percentage of occurrence, where a process makes up for over 1 % of the total mass change, is used as a second metric. The outcome of this is shown for all processes in Fig. 1 split into polar night (a) and polar day (b). The further a process is towards the upper right corner, the more relevant it is considered to be. One can see that there are some differences between the same processes for liquid and frozen hydrometeors. That is partially because some processes affect liquid, frozen and vapour at the same time, so the mean does not overlap in all cases. Additionally, there is numerical noise, which is why a minimum threshold for the tendency of $\frac{\Delta Q_{proc}}{\Delta t} > 10^{-18}$ kg kg^{-1} 3s^{-1} is set. As mentioned earlier, only

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processes which contribute to phase changes are included here.

What becomes very clear from Fig. 1 a) and b) is that sublimation, deposition, and evaporation happen very frequently and also have the highest mean values. During the polar day (Fig. 1 b) it is visible that while evaporation and deposition still play a large role, sublimation has become less frequent. However, there is much less ice in general during the polar day, and most simulated clouds were purely liquid during that time. Melting, evaporation due to melting, and rain freezing all show mean tendencies above 10^{-12} kg kg^{-1} but occur below 20 % of the time, although the differences between the seasons are striking. During the polar day, rain freezing and melting increase in importance, possibly due to the difference in temperature regimes, which allows more precipitation to melt or more liquid precipitation to occur, which can then freeze. Ice and liquid sources via nucleation tend to occur quite seldom, as one can see from the CCN activation (CCN act., in Fig. 1) and the homogeneous & heterogeneous nucleation (Hom. & Het. nuc. in Fig. 1). Using the mass change as a metric for nucleation can be misleading as the number of hydrometeors produced can say more about the impact of the nucleation process than the mass change. Another finding is the imbalance between condensation and evaporation. This indicates that evaporation, acting as a sink of liquid, is stronger than the source of liquid via condensation. This is likely a local feature as only the single column of Ny-Ålesund is used here. This feature indicates that the microphysical processes may also have a strong location dependency. For instance, in Ny-Ålesund, the air over the fjord is more moist than over the land (Kiszler et al., 2023), which may cause more evaporation over land if a cloud is advected there. Nevertheless, the message in Fig. 1 is clear that the phase changes between liquid and vapour, as well as frozen and vapour, dominate, while processes contributing to phase changes between liquid and frozen are not as relevant.

3.2 Regimes of phases

To get an overview of the cases used for the second part of the analysis, it is beneficial to understand which temperature (T), vertical velocity (w), and ice/water saturation (S_i/S_w) regimes exist for the occurrence of the hydrometeors. These variables were chosen as the microphysical processes are directly connected to them. For the analysis, we will exclusively consider grid points identified as cloudy.

An overview of the distributions of the T, w and S_i for the polar night (PN) and polar day (PD) are given in Fig. 2. The polar night temperature ranges from -32 to 2 °C with the mean at -14 °C. In contrast, the warmer polar day varies less (-22 to 8 °C) and has a mean value of -2 °C. The vertical velocity is narrowly arranged around 0 m s^{-1} for both polar night and day, and both the polar day and polar night low variation (standard deviation: PD 0.35 m s^{-1}, PN 0.29 m s^{-1}). Extremes, which happen very rarely, are found more in the upwards motion, with the overall maximum at 6.43 m s^{-1}. The saturation with respect to ice does not reach as high values during the polar day as during the polar night.

As mentioned in Sec. 2.1, the hydrometeor types are split into frozen and liquid masses. Of the total 26.3 days of low-level clouds during the polar night, almost all contain periods with frozen hydrometeors (25.4 days), and slightly more than half

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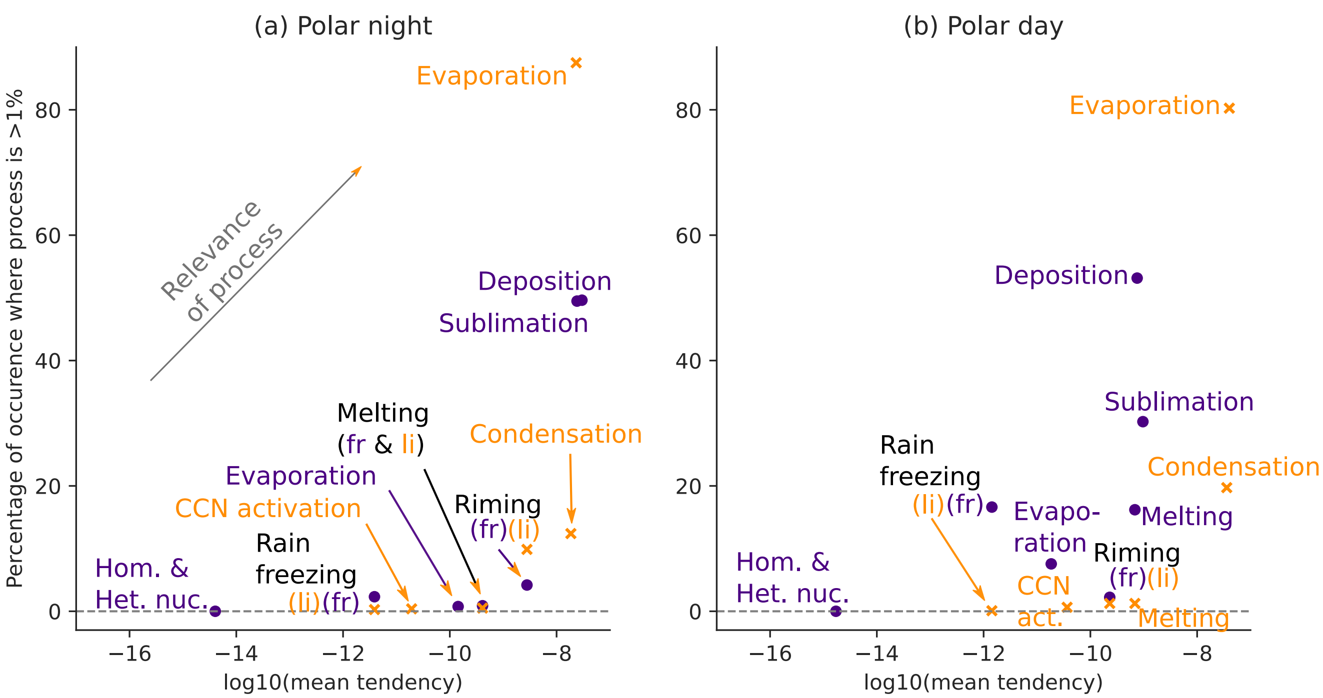

Figure 1. Processes mean values and occurrence during the polar night (a) and polar day (b). Orange crosses and text indicate processes which affect the liquid phase, and purple dots and text those which affect the frozen phase.

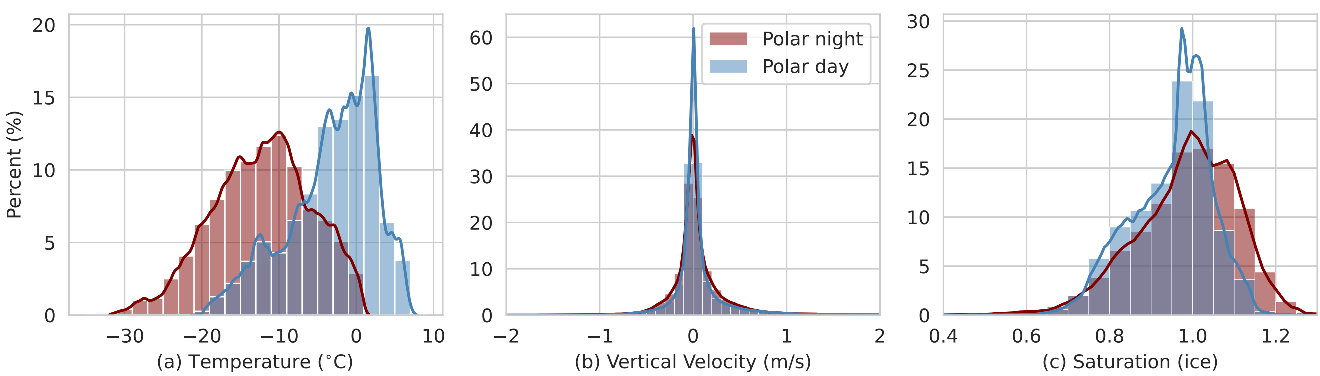

Figure 2. Distribution of the temperature (a), vertical velocity (b) and ice saturation ratio (c) for the polar night (red) and polar day (blue).

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contain liquid hydrometeors (15.5 days, 58 %). For the 37.9 days of low-level clouds during the polar day, almost all times contained liquid (96 %) while only 31 % contained ice. This is connected to the fact that liquid occurs at higher temperatures, which are more prevalent during the polar day (Fig. 2 a). To put the process rates into context, the liquid and frozen mass mixing ratios themselves generally lie between 10^{-8} and 10^{-3} kg kg-1. Another aspect to note is that similar to Shupe et al. (2008) and as theorized by Korolev (2008), we found that higher upward vertical velocities are connected to higher saturation and with that also to higher hydrometeor masses (not shown). This already hints towards potential correlations between certain processes and the vertical wind and saturation.

3.3 Dependence on environmental conditions

An interesting aspect of microphysical processes is the circumstances under which they occur. To understand more about this, the temperature, w, S_i and S_w were used to evaluate the processes in different regimes. It is worth mentioning here that sublimation and deposition can not occur at the same time as they are calculated by the same process. The same is true for evaporation and condensation. Other processes can occur at the same time. Starting with the processes affecting the frozen mass and the temperature, it can be seen that deposition and sublimation occur relatively consistently at all temperatures below 0 °C (Fig. 3 i and j) while the mean mass change decreases (Fig. 3 c and d). For sublimation the tendency spread also increases with temperature, which cannot be seen as clearly for deposition. Another process showing a decreasing tendency with temperature is rain freezing, which occurs more often for higher temperatures, but the amount of frozen mass increases with temperature (3 f and l). Rain freezing, as expected, is more efficient with lower temperatures but has less total impact the colder it is. Interestingly, a bi-modal distribution is visible in Fig. 3 e and k for riming for both the tendency as well as the occurrence. One maxima lies below approx. -20 °C, where there are altogether few cases, and one above -10 °C. This is possibly connected to the maximum saturation difference between ice and liquid water as the cloud droplet mean mass has a local minimum of around -18 °C. Melting and evaporation, due to melting, are only active above 0 °C and decrease accordingly with increasing temperatures as less and less frozen mass is available. The homogeneous and heterogeneous ice nucleation and cloud droplet homogeneous freezing happen so rarely that they are not further included. CCN activation occurs throughout all temperatures above -34 °C but is likewise seldom, especially below -20 °C. The main processes affecting the liquid mass, as discussed above, are the processes of phase change, which affect the frozen mass, evaporation, and condensation. It is intriguing that evaporation appears to be the most prominent process throughout all temperature regimes (Fig. 3), with condensation being less prominent. On the other hand, condensation has, on average, a higher mean mass change and shows much less spread consistently throughout all temperature bins.

The next variable to look at is the vertical velocity. For the frozen mass, only three processes showed a signal; therefore, this section will focus on those. One is riming, which increases with upward velocity in occurrence. This can mainly be seen during the polar night as riming is much more frequent there (Fig. 4 b). The riming tendency may suggest an increase with upwards velocity as shown in Fig. 4 a), although the fact that only 1 % of the cases are above 1.2 m s^{-1} makes this slightly speculative.

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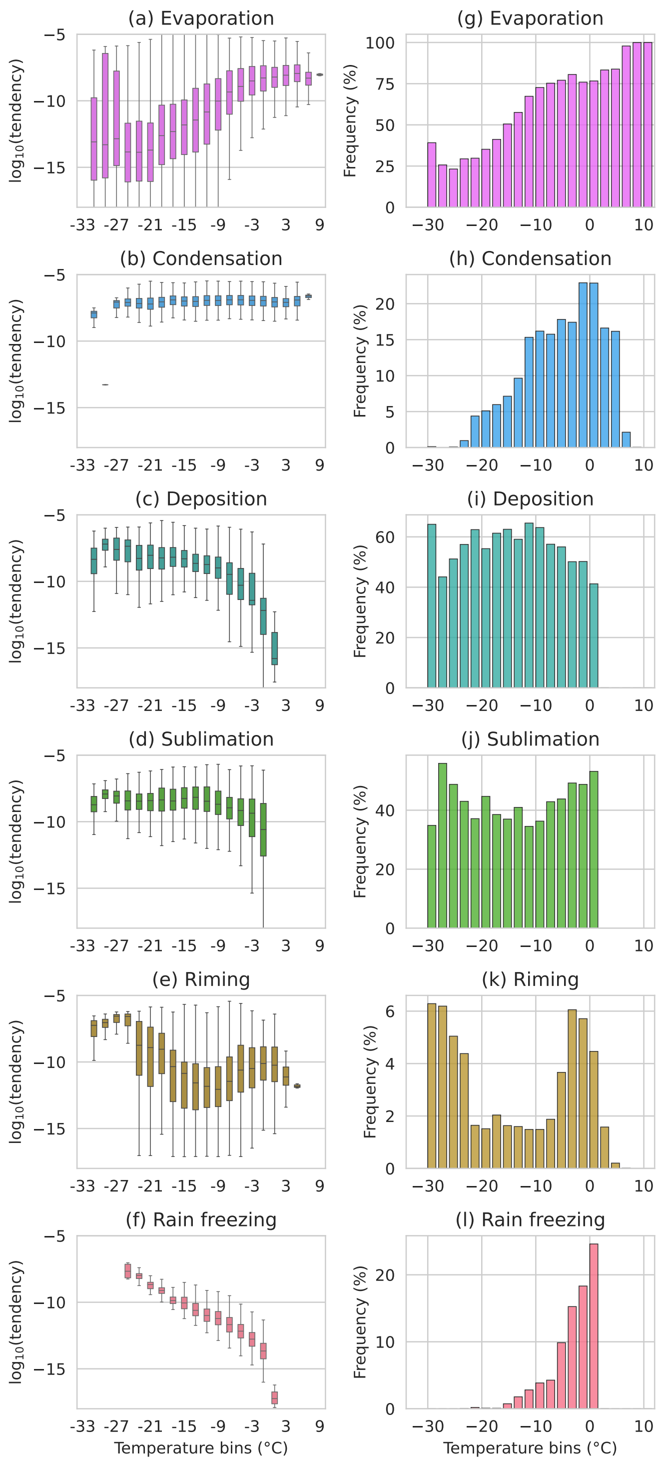

Figure 3. Temperature dependence of microphysical processes. Left column: box plots for temperature bins. Right column: Occurrence for each temperature bin. The data includes the polar night and polar day, and bins of 2 °C are used.

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If one discards the lowest and highest 1 % of the vertical wind speed, then the decrease of sublimation with upward velocity and its increases towards higher downward velocity can be seen (Fig. 5 a, white areas.). For sublimation, no difference in the behaviour between polar night and day is found. For deposition, one would expect the opposite behaviour, but as visible in 5 b), combining the polar day and polar night, such behaviour is not completely obvious. Interestingly, for deposition, a difference in its behaviour with w can be seen between polar night and polar day. The deposition frequency increases with upward velocity clearly for the polar night (Fig. 5 c). This behaviour is not so clear for the polar day (Fig. 5 d), where deposition seems common for downward motion. Additionally, the deposition rate during PD does not show a strong dependence on the vertical velocity (not shown), although previous observations show a decrease of ice mass with downward motion (Shupe et al., 2008). Reasons for this behaviour could be the lower number of frozen cases during PD or the differences in temperature range. Another reason could be differences in the vertical structure of the boundary layer and potentially increased moisture in the lower layers due to the fjord by Ny-Å. One must keep in mind that the vertical wind is very narrowly distributed around 0 m s^{-1}, and only a few absolute high values exist. To study this further, other types of clouds that have stronger vertical velocities by nature are more suitable. For the liquid mass, similarities exist between evaporation and sublimation, as both show a decrease with upward velocity. Condensation resembles the deposition more strongly and increases with upward motion. The CCN activation is, by definition, dependent on the vertical velocity. Therefore, the increase with higher upward velocity, which we found, is as expected.

The next aspect is the saturation with respect to ice and water. Processes that change the frozen mass are evaluated against S_i. Here, riming stood out again. It can be seen in Fig. 4 c and d that riming increases with saturation in both occurrence and mean tendency. This fits the increase of riming, which was described for higher upward velocities as the saturation of the rising air can increase. Some processes depend, by definition, on the saturation, for instance, deposition/sublimation and condensation/evaporation. The signal found for these processes showed evaporation and sublimation below saturation and condensation and deposition above saturation, which was, therefore, expected. What was noticeable, though, was that the tendency of condensation showed a higher mean in combination with a much smaller spread in comparison to evaporation. It was generally an interesting finding that some processes, such as condensation and rain freezing, showed much less spread in their tendency than others.

3.4 WBF in mixed-phase clouds

The introduction mentions that the Wegener-Bergeron-Findeisen process can be a reason why models have too little super-cooled liquid, impacting the representation of MPCs. As shown in Kiszler et al. (2023) also in ICON-LEM, the amount of liquid-containing clouds is underestimated. Therefore, we want to go beyond evaluating single processes and demonstrate, using the WBF process, how the process rates tell us more about intertwined processes in clouds. In the previous sections, it became clear that evaporation occurs frequently. The hypothesis is that this evaporation could partially be increased as part of the WBF process. This could suppress the production of liquid in the first place or decrease the amount of liquid in a mixed-phase cloud. To see if the WBF process can be found for the data in this study, a subset containing only mixed-phase clouds

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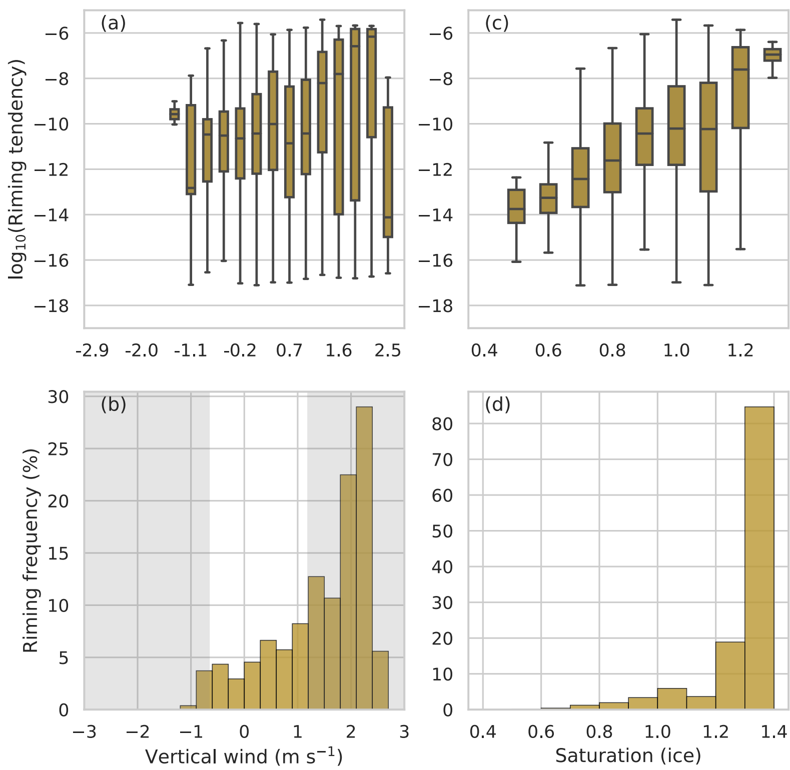

Figure 4. Dependence of riming on the vertical wind speed (left column) and the saturation with respect to ice (right column). The upper rows show the distribution of the riming tendency per bin as boxplots. The lower row shows the frequency of occurrence per bin. Bins of 0.1 are used for the saturation and 0.3 m s^{-1} for the vertical wind. The grey shaded areas indicate each the lowest and highest 1 % vertical wind speeds.

was produced (frozen mass and liquid mass both above 10^{-8} kg kg^{-1}). Then, all points where evaporation occurred were selected and split into two sets. One has cases where deposition occurs simultaneously and where it is, therefore, sub-saturated with respect to water and saturated with respect to ice. The other set has cases where no deposition occurs.

In Fig. 6 a), the distribution of the evaporation tendency for both evaporation sets is shown, and one can clearly see that they differ strongly. For the cases where deposition is happening at the same time as evaporation, the evaporation tendency is generally much larger than when no deposition is occurring. It should be kept in mind that this is a logarithmic scale, where two orders of magnitude make a large difference in the amount of liquid evaporating. In Fig. 6 b) and c), one can see the distributions of frozen and liquid masses when deposition and no evaporation is occurring and when deposition and evaporation are occurring simultaneously. Here, too, there are clear differences between the distributions, showing a shift towards higher frozen masses when deposition and evaporation occur at the same time. At the same time, the liquid mass distribution shifts towards lower values when both processes occur. In Fig. 6 c), the tail of the liquid mass, which is visible for the deposition

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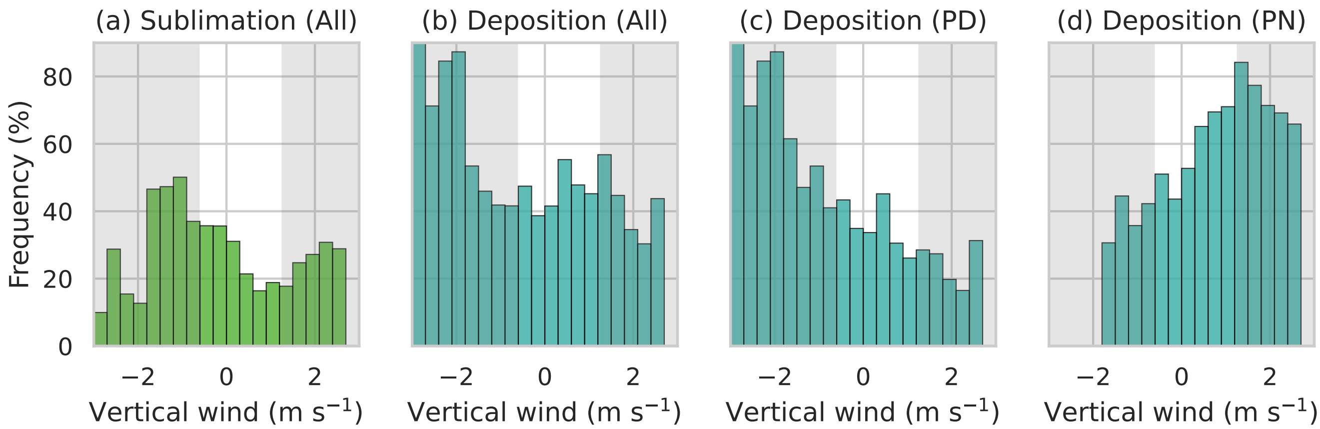

Figure 5. Occurrence of sublimation (a) and deposition (b-d) with vertical velocity (bin width: 0.3 m s^{-1}). Sublimation is shown for polar day and night (a), deposition for polar day and night (b), the polar day (c), and polar night (d). The grey boxes mark the lowest and highest 1 % of the vertical wind.

and evaporation cases, is due to rain, which often occurs in subsaturated layers as it falls. Combined, this demonstrates a decrease in liquid mass while there is an increase in frozen mass for cases where deposition and evaporation occur at the same time. For both Fig. 6 b) and c), we found the difference in the distributions to be statistically significant. This is also visible in the difference in mean values for both processes. When both processes occur at the same time, the average deposition rate experiences a one-order-of-magnitude increase ($9.8 \cdot 10^{-9}$ to $3.9 \cdot 10^{-8}$ kg kg^{-1}), while the average evaporation rate also increases with the same order of magnitude ($2 \cdot 10^{-8}$ to $1.3 \cdot 10^{-7}$ kg kg^{-1}). This suggests that a significant amount of water transitions from liquid to vapour and then to the frozen phase via the WBF process. It would be interesting to explore the sensitivity of the WBF process to changes in the process rates further. Such analysis is beyond the scope of this study, but it is worth noting that the developed methods are readily usable to perform such sensitivity studies.

4 Discussion and conclusions

This study evaluates the microphysical processes of the two-moment microphysics scheme from Seifert and Beheng (2006) as it is implemented in ICON. The area of focus is Svalbard, and only low-level clouds are selected for the analysis. Using a wrapper to run the microphysics scheme offline as a diagnostic tool, the process rates per timestep are written out. In total, eight months, four polar night and four polar day, are simulated. The goal is to determine which processes play the largest role in the phase transitions in Arctic low-level clouds and in what way they depend on temperature, vertical velocity and saturation.

It was found that the dominating processes are phase transitions between liquid hydrometeors and vapour, as well as frozen hydrometeors and vapour. The results suggest one possible approach to improving the representation of low-level mixed-phase

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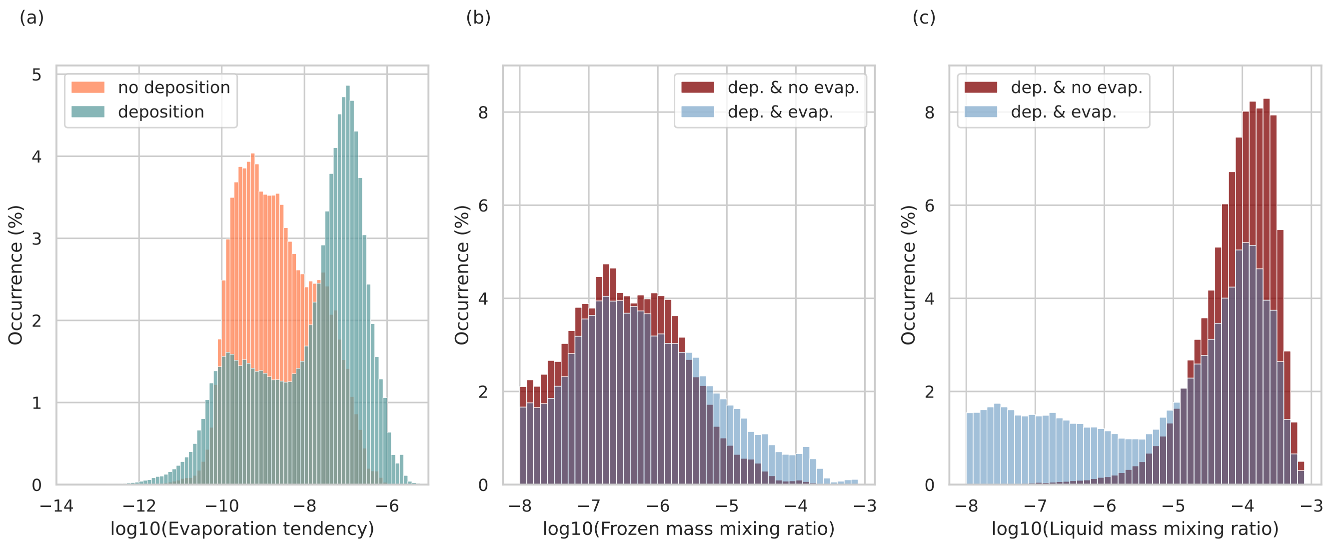

Figure 6. Histograms of the logarithm of evaporation tendency (a), frozen mass (b) and liquid mass (c). a) Liquid mass change due to evaporation in each timestep (evaporation tendency) for MPCs where no deposition occurs (orange) and where deposition occurs (green). b) Frozen mass for MPCs where deposition but no evaporation occurs (red) and where deposition and evaporation occur simultaneously (blue). c) is analogue to b) but shows the liquid mass.

clouds in the Arctic could be to adjust the processes of evaporation/condensation and deposition/sublimation. Another approach could be to increase the activity of processes which are currently less active, as these may not be active enough. Further, the differences between polar night and polar day showed the importance of evaluating a large dataset. For instance, rain freezing impacted the frozen mass during the polar day much more than during the polar night. It is worth mentioning that nucleation processes only minimally change the mass directly, but the numbers of activated CCN and INP have an impact on other process rates. Fan et al. (2017) showed this in a case study for orographic clouds where evaporation became stronger than condensation for higher aerosol concentrations, whereas for lower concentrations, the process rates were similar. Therefore, although changes to evaporation/condensation and deposition/sublimation likely will cause large hydrometeor mass changes, the interaction between processes also plays an important role.

We further explored how each process behaves in different thermodynamical regimes. Temperature is one important factor that determines the importance of a process. For instance, Fan et al. (2017) found that for warm orographic MPC riming was similarly important for the snow formation as deposition, but for cold orographic MPC deposition was clearly more important. In this study, differences are visible between the polar night and day. We found that melting and rain freezing play a larger role during the polar day while riming decreases in importance during that time. This dependence on temperature was further evaluated, and it could be seen that processes that change the mass phase between liquid and frozen show a stronger temperature dependence than those involving vapour phase transitions. The strongest temperature dependence was visible for rain freezing,

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which showed an increasing occurrence with increasing temperatures, while the mean frozen rain mass decreased. Interestingly, the distribution of riming for both occurrence and mean mass change in different temperature regimes was bimodal, showing a minimum between -20 and -10 °C. The connections between the process rates and the vapour saturation and vertical wind were not as clear. This can partially be attributed to the narrow range of values for these thermodynamic variables given in low-level Arctic clouds. The clearest signal, in this respect, was the increase of riming with increasing upward velocities. This could be connected to the larger production of liquid in updrafts where the WBF process is not active (Ervens et al., 2011; Korolev, 2008).

Going a step beyond single process rates, we demonstrated how the combination of process rates can teach us more about intertwined processes. Here, we looked at the Wegener-Bergeron-Findeisen process, where liquid water evaporates and then deposits on ice due to the lower saturation of ice below 0°C. For this purpose, only mixed-phase clouds were selected. The evaporation tendency was evaluated in combination with the frozen and liquid mass, and the results suggest that a notable amount of mass follows the WBF pathway from liquid to vapour to the frozen phase. Reducing this amount may be a way to reduce the underestimation of liquid-containing clouds found in a previous study (Kiszler et al., 2023).

As stated above, there are limitations to our approach, which might make it less insightful for cases where advection dominates the cloud hydrometeor composition, for instance, in deep convective cases. Nevertheless, when focusing on low-level clouds in the Arctic, this approach provides valuable insights in regard to the processes inside the clouds, as demonstrated in this study. Additionally, the regimes of vertical velocity and temperatures studied here are limited to those of low-level clouds in the Arctic. Therefore, to create a broader picture of the microphysical processes in other cloud types, further studies, including stronger vertical velocities and larger temperature ranges, are necessary. This could, for instance, substantiate our findings in regard to the increase of riming with higher upward vertical velocities.

There are further factors that impact the process rates, as mentioned in the introduction. These include aerosol concentrations, which can strongly impact the hydrometeor composition and cloud lifetime (Kalesse et al., 2016; Eirund et al., 2019). In this study, the CCN and INP are treated as maritime, which is more accurate than the default continental setting in ICON but still not completely correct. CCNs and INPs are another large area of active research, which is why this study focuses on the processes independently of aerosol influences. An interesting study would be, though, how tweaked CCN and IN settings impact the process rates using the approach presented here. Using the process rates and looking into the regimes where different processes occur has shown that this method is also valuable for studying individual processes in greater depth. Being able to quickly change a process setting and get an idea of what might change in the model has proven easy and reliable. This encourages continuing to use tools such as this wrapper, which simplifies the untangling of complex cloud microphysics schemes.

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Code and data availability. The microphysical wrapper code is stored on the DKRZ Gitlab. It includes ICON code and is therefore only available on request for anyone with an ICON license. The ICON model code is available for institutions or individuals under a licence: https://code.mpimet.mpg.de/projects/iconpublic/wiki/Howtoobtainthemodelcode. The process rates, low-level cloud selection and meteograms are available on Zenodo with the DOI: 10.5281/zenodo.10117706. A GitHub repository containing the code necessary to reproduce the results can be found here: 10.5281/zenodo.10341631

Author contributions. TK carried out the wrapper implementation, data processing, and method development, created the visualisations and prepared the manuscript with contributions from all co-authors. VS and DO contributed to the conceptualisation, research supervision, and discussion of results.

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