<u>Answers to the reviewers of the manuscript egusphere-2023-2986 (round 2)</u>

We thank the reviewers for taking the time to review this manuscript a second time. The provided comments and questions regarding our study and it's presentation are appreciated. Based on the suggestions by the reviewers and the editor, we have updated our manuscript and believe that the changes have further improved the manuscript.

General remarks:
Based on the feedback by the editor we have reformulated the last sections of the introduction and made some changes in the summary, to make it clearer what the relevance of this study is. Further, the biggest changes made, are aimed at clarifying one major discussion point which has been raised. This was the discussion of the WBF process and why the evaporation and deposition rates are not in equilibrium. To address this aspect, changes have been made in the method, results and discussion sections.

Line numbers refer to the revised manuscript where the changes are not marked.

Reviewer 1:

Recommendation: Accept with minor revisions.
Comments to Author(s):
Manuscript Number: egusphere-2023-2986
Manuscript Title: Microphysical processes involving the vapour phase dominate in simulated low-level Arctic clouds
Authors: Theresa Kiszler et al.
Overview and general recommendation:
The authors have made significant improvements to this manuscript. I find that nearly all my concerns have been addressed. My remaining comments are listed below. Beyond the minor corrections, my comments are largely concerned with how the authors discuss the imbalance between evaporation and deposition when the WBF process is active. Specifically, evaporation exceeds deposition, indicating a cloud state that is constantly losing water. The other reviewer raised a very similar point in their comment on the study's choice of location and the authors have partly addressed this in their response. However, I think that the results regarding the WBF process will be of greater value when discussed in the context of: a) the evaporation-deposition imbalance indicating a strong cloud water sink that may exceed the WBF mass rate itself, b) how the choice of location likely causes this behavior and the relevance of these results to Arctic regions characterized by high sea ice cover (as opposed to Svalbard).

Comments are formatted as:
Line number in trackchanges document: "Text"
Specific Comment

182-183: "Further…"
I think that a slightly longer explanation is needed here for readers to understand this. Additionally see later comments regarding the WBF values and why they sometimes exceed the deposition and evaporation values.
From the reviewers comments, it has become clear that more explanation is necessary on how exactly the evaporation and deposition are implemented in the model. This is a relevant detail, therefore we have added more information on this in l. 180 *"An additional process which is not directly implemented in SB, but is analysed in this study, is the WBF process. As evaporation and deposition are needed simultaneously for the WBF process, it is possible to use their rates to compute the WBF rate. During WBF events, the second call to the saturation adjustment happens*

in an atmosphere that has been deprived from moisture due to deposition on ice and hence causes additional evaporation."

184-202: Whole paragraph.
The authors have done a great job introducing this important point early on. Given that the results presented here may depend strongly on location, I think it would be useful for the authors to discuss how location may affect their results in the discussion.
We understand the interest in the location dependency. We want to highlight though that we do not have an overview of the process rates in other locations, as so far generally only single case studies have been looking into the process rates to the extent we have done it here. It would be very beneficial if more studies evaluating process rates directly and not by proxy (i.e. number and mass concentration changes) would exist. As this is not the case we mention the location dependency but do not debate this in detail.

Specifically: Is the result that the WBF process is deposition-limited specific to this case over land?
We cannot answer this as we do not look at other model columns.
Given that many studies of low-level Arctic mixed-phase clouds is often focused on their ability to persist over long time periods, is this case where at least 33% of the clouds are evaporating representative (line 234)?
Here it is worth highlighting, that we have looked at 8 months of data and therefore argue that our finding are representative for the simulated clouds above Ny-Alesund during the PN and PD. The finding of such frequent evaporation could explain why we have found too little liquid in simulated clouds at Ny-Alesund in comparison with observations. It is worth pointing out that we are not trying to show what happens in Ny-Alesund in reality but what happens in the model and give ideas why the simulated clouds could differ from the reality.
And if the evaporation exceeds deposition when the WBF process is active are these cases more representative of the WBF process sustaining clouds or cloud evaporation/glaciation?
If the WBF process is occurring this is a glaciation process. It is possible that excess evaporation is decreasing the cloud mass though at the same time. This imbalance between evaporation and deposition is discussed below.
I think that this kind of discussion will help readers understand how this study fits into the broader literature around Arctic mixed-phase clouds.

249: "demonstrates visualizes"
Wording error here.
Thank you, corrected.

256-257: "This shows…WBF process."
Can you comment on the evaporation rate increasing more than the deposition rate (and that generally the evaporation rate exceeds the deposition rate)? Similar to a previous comment, the WBF process shifting liquid to ice is mostly discussed here but the high evaporation rate indicating instability seems quite important as well.
This is indeed a relevant aspect where the implementation details help to understand what happens inside the model and as described above we have expanded the explanation of the implementation. The evaporation is computed by the saturation adjustment which is called twice, once before and once after the other microphysical processes are called. In addition to showing this is in the supplement figure A1, we added this also in the process description in line 175 *"The saturation adjustment is run once before and once after the other microphysical processes (see Fig. A1)"* Therefore, not all of the evaporation in each time step may be directly connected to deposition. Evaporation could occur twice while deposition can only occur once. To make this clear the

following sentence was added in l 246“ *The difference in rate change could be connected to the microphysics implementation, where the saturation adjustment is called twice in contrast to the deposition, which is called only once.* “. This is something where there exists further study potential into what impact the numerical implementation may play and also which cloud conditions allow for varying relative process importance. This is because deposition and evaporation are ultimately the result of a complex interplay of air humidity, temperature, and the properties of ice particles and liquid drops. We suggested that also the latent heat release resulting from the net glaciation caused by WBF could cause additional evaporation. Although that goes beyond the scope of this paper we believe it is worth pointing out so we added a discussion on this in the results l. 391 “*The finding, that evaporation increases substantially more than deposition was partially attributed to the implementation of the microphysical processes which favours excess evaporation when WBF is active. Also, the thermodynamics of WBF is expected to cause additional evaporation, but it is not possible at present to quantify this effect. Nonetheless, it is suggested that the tools and methods developed in this study can help making quantitative analysis of such effects and uncover the intricate relationships among moisture, temperature and cloud particle properties that affect the WBF process in numerical models.* “

273-276: “We hypothesize…set in.”
Interesting! So there may be an indirect effect of riming/rain freezing/secondary ice processes that enhances the WBF effect at relatively high temperatures?
Yes, it is interesting that there seems to be a connection. It must be taken into account though that the cloud occurrence also plays a role in fig. 4 as we just normalized by temperature there. We have also looked into whether the fact that there are more clouds around -3°C is the cause for this peak but even when normalizing also with respect to cloud occurrence, we can see that deposition behaves differently during PD than during PN and does not show the continuous decrease which we would expect towards 0°C. We have mentioned this now in the text in line 167 , but have decided against changing the figure as the figure which is normalized with respect to temperature and cloud occurrence could easily be confusing for readers.

296: Figure 4
If the WBF process is taken as the minimum of deposition and evaporation, how can it exceed either of them in this figure and else? I may be misunderstanding so an explanation to the readers could be helpful here.
The reviewer points out, that the explanation is not fully clear. We agree with this and have changed the caption to make this clearer “[…] The process distributions are normalized with respect to temperature but not cloud occurrence.”.
Each process distribution is normalized, hence its integral over the temperature range is 100%. So if the WBF process distribution is focused slightly more around a specific temperature range, the percentage of its occurrence will be higher than deposition and evaporation. The calculation can be found in the following jupyter notebooks in the mentioned github repository:
/notebooks_figures/fig_03_04_wbf.ipynb and /required_modules/process_class.py

351: “This we only found partially.”
Check wording here.
Sentence corrected, thank you.

427: “simultaneaously”
Correct to “Simultaneously”.
Corrected, thank you.

425-428: “When combining…tendency.”

I struggled with understanding the authors' meaning here and recommend revising these sentences.
These sentences were reformulated to improve the clarity. L 382 "One such process interaction is the Wegener-Bergeron-Findeisen process, where liquid water evaporates and then deposits on ice due to the lower saturation of ice below 0°C. To evaluate the WBF process, we selected cases where deposition and evaporation occurred simultaneously and used the minimum rate as approximation for the WBF tendency."

429-431: "Additionally,…liquid mass."
What caused the 10x increase in evaporation? I don't think that I agree that it is the occurrence of the WBF process because the increase in deposition is much less, right? Doesn't this indicate that the WBF process is already strongly limited by the deposition rate? Would decreasing the deposition rate as the authors recommend just lead to the cloud evaporating instead of transitioning to ice? I understand that there is additional complexity here (the air may saturate earlier), but in general if evaporation increases more than deposition when both are active I would expect that enhanced evaporation to dominate the cloud changes.
We appreciate the interest the reviewer has shown in this. To address these questions several adjustments in different places of the text have been made and are listed in the above two comments which also refer to this topic.

464-465: "Specifically…formation phase."
See previous comments. The importance of the study's location and regime of cloud decay is closely connected to the imbalance between evaporation and deposition seen in the process rates and WBF process analysis. I think that linking these concepts together is a critical aspect of this paper and should be included in the discussion.
It is indeed noticeable that the liquid clouds generally seem to be in decay. We agree that it is very important to discuss the location aspect as well as this evaporation-deposition imbalance. At the same time we would disagree in linking the WBF rates too strongly to the location. We believe the imbalance of evaporation and deposition in WBF cases could be caused by the implementation. It would require further research into different locations and cloud types in our view to expand the picture. Such progress is currently being made (for example Omanovic et al., 2024).

Reviewer 2:

I appreciate the large effort that the authors put into revising their manuscript. I certainly think that it reads better now. That said, I do still have concerns about the discussion and the utility of the results.

Major Comments
1. A main conclusion that appears in the abstract and the conclusions is that "the dominating processes are phase transitions between liquid hydrometeors and vapour, as well as frozen hydrometeors and vapour." I agree that the results showed this, but isn't this just as we would have expected? For these clouds where presumably precipitation is typically minimal, the only way to make or destroy a cloud is through phase transitions with vapor. Unless all clouds were created as liquid and froze to make fully ice clouds (in which case, vapor transitions would be equally important to liquid-solid transitions), vapor transitions will by definition be more important than liquid-solid transitions.
We thank the reviewer for their critical view on this and agree that this may sound like a basic finding. We would like to highlight though that for MPC it is not clear which processes exactly create the phase-partitioning. In this study we put numbers to the expectations and we show for example that although one may expect riming for instance to be very important, that this is not the

case here. This study takes our current understanding of Arctic low-level clouds and looks at how their processes are implemented and digs deep into the details of what exactly is happening. Using the process rates of the model, we show what happens and in addition link this to the lack of simulated liquid containing clouds in the model.

2. In lines 326-330, the authors try to make suggestions for improving phase partitioning in models. It's hard for me to see how these suggestions follow from the results and to be honest the suggestions mostly boil down to "try everything." Since the results themselves are model-based and we have no comparison to observations, it seems difficult to say what the problem is with models (presumably the authors mean global models at much coarser resolution – this should be explicit). I think a better and more useful discussion would be about how others could use your results to evaluate their models and identify weaknesses.
The reviewer wishes for more detailed suggestions about how to improve the model. In the discussion we provide several suggestions of what can be addressed as we know that the problem is the missing liquid water in Arctic clouds in ICON. We highlight that we believe the evaporation/condensation (saturation adjustment) and the deposition/sublimation are relevant targets to address. Additionally, we point out that potentially other processes (those which are less frequent) could be increased in efficiency. We cannot get more specific here because there are many unknown factors which are for instance the aerosol settings. The entire results of what we found can be used though to guide efforts in improving the representation of low-level clouds in ICON. The suggestions for specific process changes are based on our findings for each process rate.

Minor Comments

ICON Simulations: Can the authors say a little more about the simulations? It says that each is run for 24 hours, but how many simulations are there? How are they distributed over the year?
The simulation are semi-operational and run for every day (we added this in the manuscript). From this study we selected some data, as mentioned in section 2.2 "Selected data". As it states in Line 109 "Therefore, two sets of data are used. One covers the polar night (PN, November 2021 - February 2022) and one the polar day (PD, May-August 2021).". We then list how many days worth of low-level clouds we are evaluating. We believe adding another number to list the number of days the accumulated 8 months have in total will cause confusion because we do not analyse each day but only times with low-level clouds. Therefore, we will leave this as it is.

WBF frequency: Have other studies tried to quantify the WBF frequency in clouds? If so, can you compare your results to these studies? If not, maybe this is something to highlight more explicitly as a novel contribution of this study?
Other studies have tried to quantify the WBF process for instance using proxies such as the hydrometeor mass and number concentrations. This can be difficult to compare though as different locations, cloud types and timescales are evaluated. One paper which we have added now is by Omanovic et al. (2024) and complements our work. So far though, there have been no such detailed analysis of the process rates for a specific location over such a long period. This is where we can provide novel insights.

Line 69: The authors state that the simulations underestimate liquid water by 30%. Can they comment on how this shortcoming impacts the analysis? It seems like this is a pretty large model bias for a study that is trying to understand phase partitioning better.
We are glad that we made the main shortcoming of the model so clear. This said, this study was motivated in parts exactly by this underestimation of the liquid water. We want to understand what could be causing this, as ICON is not the only model that struggles with the representation of supercooled liquid. Therefore, this is not a shortcoming in our eyes but the reality of atmospheric models in their current state.

Line 182: "The finding that all cloud types seem to be in the process of decay, where processes acting as sinks are dominating, is potentially a local feature as only the single column of Ny-Ålesund is used here." Why only "potentially" a local feature? I mean, it seems like it can't possibly be true that all clouds are decaying everywhere. Surely somewhere the clouds are forming.

We agree that the clouds must form somewhere. The "potentially" refers to the aspect that a primarily decaying phase of clouds also could happen elsewhere. Further, and most importantly, we do not know exactly why this is what we found in Ny-Ålesund and therefore we want to be careful with our wording.

Line 206: For clarity, specify that deposition and evaporation occur simultaneously. And in the following line, the second set is presumably evaporation with no deposition?

Line 227 states "To evaluate this aspect the subselection of MPCs was evaluated where evaporation was occurring (75 % of MPC cases). This set was split into two sets. The WBF set consists of cases where deposition occurs simultaneously and where it is, therefore, sub-saturated with respect to water and saturated with respect to ice.". To us it is not clear how this could be more explicit as WBF is defined as evaporation and deposition at the same time. Further it states that "deposition occurs simultaneously" so in addition to evaporation, which is occurring in this data set as the sentence above states.

Is it fair to say that this second set is where we have evaporation and sublimation? Likewise, does "no evaporation" mean "condensation"?

Yes, "no evaporation" generally means condensation and "no deposition" means sublimation as we are not in an equilibrium where nothing would happen. As we use thresholds the cases of "no evaporation" or "no deposition" are defined as all cases which are below the given threshold of 1e-18.

Line 226: We "found that the WBF process seems to correlate more strongly with deposition than with evaporation (Fig. 4)". Since the WBF rates is defined as the minimum of evaporation and deposition, this results says that the deposition rate is typically less than the evaporation rate. Doesn't this say that the combination of the two is acting to humidify the air and shut off the WBF process? This seems surprising to me since I tend to think of glaciation via the WBF mechanism as a runaway process rather than one that attempts to bring water back into equilibrium. Or does an imbalance in latent heating prevent this shutoff? I'd have to think through it a little more. I guess I'm generally wondering if more could be said about this result which seems potentially counterintuitive.

The reviewer brings up an interesting thought here. We found that there seem to be two regimes where the WBF is limited by either deposition (which seems more common) and where it is limited by evaporation. These regimes are linked to the amount of liquid in the cloud and this can be understood better when looking at the supplement figure B1. It could be that there is a time-lag whereas the evaporation is faster than the deposition.

Another aspect to mention here is that the WBF process is not explicitly modeled in the cloud scheme. It rather results as a direct consequence of the implementation of the microphysics which allows the saturation adjustment to be called twice in each timestep in contrast to the deposition which is only called once. This causes the WBF to emerge as a way to restore the water equilibrium as the reviewer suggested. We realize that this was not so clear in the text and have added more explanation on this in l 180 *"An additional process which is not directly implemented in SB, but is analysed in this study, is the WBF process. As evaporation and deposition are needed simultaneously for the WBF process, it is possible to use their rates to compute the WBF rate. The saturation adjustment, which provides the evaporation rate, is computed twice in each timestep in contrast to all other microphysical processes. During WBF events, the second call to the saturation*

adjustment happens in an atmosphere that has been deprived from moisture due to deposition on ice and hence causes additional evaporation."
and explained how this may cause an imbalance between evaporation and deposition in l 244 *"The difference in rate change could be connected to the microphysics implementation, where the saturation adjustment is called twice in contrast to the deposition, which is called only once and the physics of the WBF process. Considering the typical thermodynamic situation characterizing WBF, the atmosphere is subsaturated with respect to water and supersaturated with respect to ice. This causes evaporation to occur during the first call of the saturation adjustment, providing more moisture to be deposited into ice as a result of the microphysics scheme, then during the second call of the saturation adjustment the atmosphere tends to return to the state it was before deposition happened. Because of this, intuitively evaporation would be higher than deposition."* Finally we discussed that the imbalance in latent heat should actually favor higher evaporation rates. "*Additionally, if deposition and evaporation tendencies would be the same there would be a net release of latent heat causing the equilibrium to shift towards additional evaporation.*"

Line 231: "As deposition should decrease with increasing temperature the peak at higher temperatures". It's not obvious to me why the deposition should decrease with increasing temperature, although I see later that you show this result explicitly. I suppose that supersaturation wrt ice tends to be higher at lower temperatures, but there's also less water vapor available. A quick reasoning for this statement could be helpful, especially for the reader who is not an ice microphysics expert.
Deposition is implemented to be dependent on the temperature and saturation. In case of higher temperatures the required supersaturation wrt ice increases and therefore more moisture would be required to cause the same amount of deposition as at a lower temperature. As the reviewer observes, with increasing temperatures above -15°C, we found the deposition rate to decrease. We added that this statement is shown later to make the statement more clear: l 265 *"As deposition should decrease with increasing temperature (shown later), the peak at higher temperatures was not expected."*

Line 264: "evaporation dominates throughout all temperature ranges where liquid occurs" Given that the mass budget is not closed, do the authors think this is a general conclusion or only one that is specific to this dataset?
This is specific to the dataset. We cannot reliably generalize the conclusions of this analysis to the larger Arctic environment or even different climate regimes, but the developed tools can be easily used for data from different locations and/or time of the year, allowing to extend the study to diverse conditions.

Line 295: "the WBF process is to a certain extent expected for downwards velocities" Why is it expected? Shouldn't downward velocities promote subsaturation with respect to both liquid and ice? Perhaps the authors just mean that the WBF process is possible in downdrafts?
This is expected when the environmental conditions are favourable for the WBF process, which means for slight downwards velocities given the right saturation vapour pressure and temperature. Downwards velocities can promote subsaturation with respect to both liquid and ice but there are certain thresholds for this to occur. In the cited Korolev (2008) paper the theory behind this is elaborated as the critical vertical velocity depends on multiple factors and there are several regimes which can be differentiated.

Line 343: "it seems like the deposition tendency drives the occurrence of the WBF process" I'm not exactly sure what this statement means. The authors showed that the WBF rate reflected the deposition rate, but since the WBF rate is the minimum of deposition and evaporation, doesn't that mean the evaporation rates are higher? I'm not trying to say that

evaporation drives the WBF, just that I'm not sure that the higher correlation with deposition necessarily implies anything about what controls the WBF occurrence.

The reviewer pointed out that this sentence is not fully clear and we have revised it to capture better what we have found. L 385 "*Further, it seems like the deposition tendency determines the rate of the WBF process.*"

Technical Comments

Line 92: kg kg-1 formatting
Thank you, changed.

Line 194-196: Run-on sentence that is confusing.
This was indeed a confusing end of the paragraph and we have improved it in l 217:
"*Evaluating this single column, shows that microphysical processes vary strongly in their importance and depend on the location studied. It is evident that the microphysical sinks found for liquid clouds are much weaker for mixed-phase and ice clouds. Especially, for the MPCs it became clear that the WBF process acts strongly upon the liquid mass and it is therefore worth further investigating its behaviour.*"

Further minor changes by the authors:

l 20 wording: "… interest to which extent clouds play a role." → "... interest to which extent clouds play a role in this."

l 37 Corrected grammar: "… processes remains a challenge ..." -> "processes remain a challenge"

l 79 Missing lon-lat values "...diameter centred in Ny-Ålesund (Svalbard, lon-lat)..." → "...diameter centred in Ny-Ålesund (Svalbard, 78.9 °N, 11.9 °E)..."

l 114 Wording corrected: "In the analysis the temperature, vertical velocity, and ice/water saturation with dependency of different microphysical processes is discussed." → "In the analysis the influence of the temperature, vertical velocity, and ice/water saturation on different microphysical processes is discussed."

l 119 Wording corrected: "… both PN and PD, and both the PD and PN low variation ..." → " ...both PN and PD, and both the PD and PN show low variation..."

l 160 Correction: "… water vapour due to phase changes from frozen to vapour. "… water vapour due to phase changes between frozen water and water vapour."

l 226 Improved wording. "...whether the evaporation rate would increase due to the WBF process." → "...whether the evaporation rate increases due to the WBF process."

l 369 Increase clarity: "It was found that the dominating processes are phase transitions between liquid hydrometeors and vapour, as well as frozen hydrometeors and vapour." → "It was found that the dominating processes in MPCs are phase transitions between liquid hydrometeors and vapour, as well as frozen hydrometeors and vapour.

L 304 Improve clarity and shorten sentence"… which potentially indicates that it may be more strongly influenced by other factors for negative temperatures, than other processes which depend more clearly on the temperature. “ → “. This potentially indicates that evaporation may be more strongly influenced by other factors at negative temperatures, in contrast to other processes which depend more clearly on the temperature.”

l 351 Increase clarity “This fits the increase of riming, which was described for higher upward velocities as the saturation of the rising air can increase.” → “This fits the increase of riming found for higher upward velocities, as the saturation of rising air can increase.”

l 357 Increase clarity “...their tendency than others in respect to all thermodynamic variables evaluated here.” → “their tendency than other processes in respect to all thermodynamic variables evaluated here.”

Corrected subplot label references relating to Fig. 5 and Fig. 7 c and d switched in text. Added reference to C2 subplots.

Data availability statement:
Change of wording for clarity and added citation as the data set was now also mentioned in the text.

We have added a reference to the recently published paper by Omanovic et al. (2024, https://doi.org/10.5194/acp-24-6825-2024) as their results complement the discussion of our findings.