Response to Referee #1

The manuscript by Kretzschmar et al. shows a positive bias in cloud cover over the Arctic from global atmospheric model ECHAM6 with comparison with CALIPSO, and studies the possible causes of this difference, and presents their efforts to remove this bias with different parameterization in the model. The efforts include adjustment of moisture/heat exchange between surface and atmosphere, and tune of the effectiveness of Wegener-Bergeron-Findeisen process, and to allow supersaturation with respect to ice with a new parameterization of saturation water vapor pressure. The paper is generally well written and concise, which I particularly appreciate. The primary concern I see is the effectiveness of the new parameterization of the saturation water vapor pressure over both sea ice/snow and open water, which the authors may need a better presentation of their results. My recommendation is that the manuscript needs be revised prior to publication to better present the effectiveness of their new approaches.

We thank the reviewer for the constructive comments that helped to improve the manuscript.

Major comments

1. By allowing super saturation regarding to ice, the differences of low-level cloud between model and CALIPSO are somewhat reduced over sea ice/snow especially with smaller ice mixing ratio thresholds, as shown in Figure 6. The benefit is accompanied by the drawbacks that the differences over other areas become negative, with even more negative differences over open water, e.g. over the GIN seas and Barents Sea. As shown in Figure 1 and 2, such negative differences exist with original parameterization. So, the new parameterization may lead to another issue, underestimation of cloud cover, over the open water area, including the newly open water in the Arctic in summer and autumn. The authors mentioned the reduced condensation removal by precipitation may solve this, which may trigger other issues. The authors may want to clarify this in the manuscript.

The idea that reduced condensation removal by precipitation may solve this issue was purely speculative and we did not conduct sensitivity studies to this end and therefore we removed this statement from the manuscript. In the revised version of the manuscript, we try to more clearly point out why a temperature-weighted scheme for saturation vapor pressure in combination with an increased efficiency of the WBF process introduces a negative bias in low clouds. As the amount of low-level ice clouds remains more or less constant for different values of γ_{thr}, the amount of liquid clouds strongly decreases and therefore also the amount of clouds in general. The decrease in liquid clouds is mainly caused by the more efficient WBF processes which more efficiently turns liquid into ice clouds over continents compared to oceanic regions. In the standard setup of ECHAM, liquid clouds are already biased low in those regions which is even further enhanced by a more effective WBF process. As liquid clouds seem to react rather sensitively to a more effective WBF process, even minor changes of γ_{thr} can have strong effects on the amount of liquid clouds and we think that setting γ_{thr} to $2.5 \cdot 10^{-6}$ $\mathrm{kg\,m^{-3}}$ might already be a reasonable value to improve the WBF process. This value might be a good compromise between improving cloud cover over snow and ice covered surfaces by simultaneously not further worsen clouds in other regions. These new explanations are now in the manuscript in order to respond to the reviewer's remark.

2. The adjustment of surface/atmosphere heat/moisture strength seems working fine to me. In the manuscript, the authors said "For sea ice covered surfaces, ...while only minor changes in the cloud cover bias are found for summer". (Line 18- Line 23, page 7). I see the cloud cover after the adjustment agrees with CALIPSO really well over sea ice with scaling factor 5 as shown in Figure 4. The differences in winter are small, and the apparent difference in the later summer and autumn might be due to the CALIPSO shows more cloud cover over newly open water in the Arctic Ocean, while the model cloud cover are over sea ice only. This suggests this adjustment somehow works, even though the mixing is already too strong over the sea ice, as the authors discussed.

We agree with the reviewer that increased mixing seems indeed be a good way of tuning Arctic clouds. As requested by the reviewer also in one of the minor comments below, we added a new, more detailed discussion of the effect of this adjustment on liquid and ice clouds. Increased mixing was also able to improve cloud phase as the liquid bias in winter is now also reduced, which further shows that this might be a good option to improve clouds. In the revised version of the manuscript, we try to emphasize the positive effect of increased mixing on cloud cover, even though we still think that it might be questionable whether one can physically justify such a measure as the model already mixes too strongly in the Arctic with its stable boundary layers in comparison to surface observations.

3. Model has positive bias in cloud cover, especially in low-level cloud, when compared to CALIPSO. CALIPSO has low cloud amount bias when compared to surface based observations, as studied by Blanchard et al. (2014) and Liu et al. (2017). The overestimation over sea ice may be appearing as significant considering CALIPSO's underestimation of low-level cloud.

We revised the description of the CALIPSO-COCCP dataset. Section 2 now contains a more detailed description of the observational dataset (i.e. cloud detection thresholds, information on vertical resolution, phase discrimination). In the revised version of the manuscript, a more detailed review of uncertainties and issues for retrieving clouds in the Arctic using CALIPSO-GOCCP is included (i.e. lidar attenuation by liquid clouds, cloud detection thresholds that might not be representative for Arctic region and also possible effects of spatio-temporal sampling of satellite data). Nevertheless, we think that our claim of an overestimated low-level cloud fraction in ECHAM6 is valid. We compared modeled (ECHAM+COSP minus ECHAM) to observed (GOCCP minus ground based observations) cloud cover profile differences and see a similar underestimation for modeled clouds when using a satellite simulator compared to the cloud fraction from ECHAM6's cloud cover scheme. Even though comparing modeled and observed difference in cloud cover profiles is not an "apples-to-apples" comparison (because of different definitions of what is a cloud), we see that COSP derived cloud properties mimic real world issues of the actual lidar. Therefore, the reported overestimation of low-level clouds in the model is a "real" signal and not just due the observational issues in the GOCCP dataset.

Specific comments

1. Line 6 page 1, this overestimation is also due to overestimation of high-level cloud.

We added the explanation that the overestimation of total cloud cover is due to an overestimation of low- and high-level clouds to the abstract.

2. Line 21 page 2, please spell Acronym out at its first appearance, like CALIPSO; also after the first appearance, there is no need to spell it out again, like COSP.

Done.

3. Line 33-35 on page 3, I am wondering what SST and ice concentration data you used in your model run?

We use monthly observations of sea surface temperature and sea ice concentration from the AMIP II dataset. We added this to the manuscript.

4. Line 11-12 page 4, I am wondering how you are able to divide each model grid box into 40 subcolumns?

In the revised version of the manuscript we elaborate more on how those subcolums are created.

5. Line 19-20 page 4, you have model runs from 2007-2010, when sea ice extent in the late summer and autumn were significantly reduced. The cloud cover is greatly affected by this. It would be *good to have the model runs from other years without such sea ice extent changes, which was not available in this study due to the computational cost as the authors pointed out.*

The reviewer is right that this introduces a complication. But since the observations are for the same period, and since the biases are widespread, we think that the conclusions are valid. In any case, since CALIPSO and CloudSat are available only since 2006, there is no possibility to go for another period for the evaluation.

6. Last line on page 4, consider changing "higher" to "greater".

Done

7. In the 1st paragraph of section 3, you might want to point out there is underestimation of cloud cover over open water.

Done.

8. Line 11-12 on page 6, unless you show there is no humidity bias over other surface types, this claim may not be valid.

We additionally show from ERA-Interim to also have information on temperature and humidity profiles on a wider spatial scale to show that there is a difference between snow/ice covered regions and not snow/ice covered regions. Looking at relative humidity, ECHAM6 seems to generally overestimate it over the continents, but this overestimation is most strongly pronounced in those regions we observed the strongest positive biases in low-level clouds, which make us confident that this overestimation actually exists.

9. Line 18-23 on page 7, it would be interesting to see the impacts of the adjustment on liquid and ice cloud cover.

In the revised version of the manuscript, we added the impacts of the adjustment on liquid and ice cloud cover. As we already stated above, the approach of increased mixing seems promising as this measure not only reduces the cloud cover bias of low-level clouds but also addresses helps to reduce the overestimated bias of liquid clouds.

10. Line 9-10 on page 8, the differences also include bias in high-cloud.

The revised manuscript now explicitly points the reader to this fact.

11. Line 19 on page 8, "below" should be "above"

Using "below" in this sentence is correct, as we refer to condensation. Nevertheless, we see that this sentence can be misunderstood and modified it to be better understandable.

12. Line 28-29 on page 8, how about the changes in low-level clouds?

With total cloud cover, we mean total, low-level cloud cover. To avoid confusion, we now just call it "low cloud cover".

13. Line 28-31 on page 10, please reword this sentence.

Done.

Response to Referee #2

This manuscript uses satellite observations from CALIPSO to evaluate Arctic cloud cover in ECHAM6. The authors found that low liquid cloud cover in the Arctic is biased high over surfaces covered by snow and ice in the default version of the model. They investigate two potential reasons for the high bias the strength of surface heat fluxes and the impact of the Wegener-Bergeron-Findeisen (WBF) process. The authors conclude that surface heat fluxes are too strong in the default version of the model and that they can instead decrease their high bias in Arctic low liquid cloud cover by allowing for slight supersaturation with respect to ice in their cloud cover scheme, which in turn impacts the WBF process in ECHAM6. I have numerous concerns about the manuscript that are primarily related to the methodology and conclusions drawn by the authors. My comments are below.

We thank the reviewer for the constructive comments.

Major comments

The description of the observational dataset does not contain a discussion of observational uncertainties associated with CALIPSO/GOCCP. Namely, lidar beam attenuation is particularly problematic in the Arctic, where many clouds are optically thick, liquid, low-lying and precipitate snow. When compared to ground-based observations in the Arctic, CALIOP cannot see clouds in the lowest few kilometers (see e.g. Liu et al. (2017)) and the difference with GOCCP can be quite substantial especially over the Greenland ice sheet (Lacour et al. (2017)). This was also noted to be problematic in Cesana et al. (2012), and mostly affects precipitating ice underneath optically thick liquid clouds. I worry that the authors claim of a high bias in low, liquid clouds in the Arctic and their comparison for ice clouds may be inaccurate for the aforementioned reasons. The disadvantage of ground-based remote sensing observations, of course, is their lack of spatial coverage. I would still, however, recommend that the authors incorporate Arctic ground-based remote sensing observations from a few sites collocated with GOCCP to get an idea of potential biases that might impact their conclusion.

In the revised version of the manuscript, a more detailed review of the uncertainties related to the GOCCP dataset is included (i.e. lidar attenuation by liquid clouds, cloud detection thresholds that might not be representative for Arctic region and also possible affects of spatio-temporal sampling of satellite data).
Nevertheless, we think that our conclusion of an overestimated low-level cloud fraction in ECHAM6 is still valid. The GOCCP dataset is based on satellite retrievals and is not directly comparable to ground observations or to model output. In order to make our model results comparable to the GOCCP dataset we use the COSP satellite simulator. In the revised manuscript, we compare modeled (ECHAM6+COSP minus ECHAM6) to observed (GOCCP minus ground based observations) cloud cover profile differences and see a similar underestimation for modeled clouds when using a satellite simulator (ECHAM6+COSP) compared to the cloud fraction form ECHAM6's cloud cover scheme. While comparing modeled and observed differences in cloud cover profiles is not an "apples-to-apples" comparison (because of different definitions of what is a cloud), this demonstrates that COSP derived cloud properties can mimic real world issues of the spaceborne lidar. Therefore, the reported overestimation of low-level clouds in the model is a "real" signal and not just due the observational issues in the GOCCP dataset.

Furthermore, the description of the observational dataset also does not mention the vertical resolution and criteria used for phase discrimination in the GOCCP product. Were daytime and nighttime data used? What timeframe was used? Were data before prior to the change in nadir-viewing angle used? How were oriented crystals handled?

In light of this remark by the reviewer, we revised the description of the CALIPSO-COCCP dataset. Section 2 now contains a more detailed description of the observational dataset (i.e. cloud detection thresholds, information on vertical resolution, phase discrimination). In Section 3, we now also state that we use monthly averaged data for the same timeframe as the model simulations using both, day- and nightime overpasses. Concerning the change of the nadir pointing angle at the end of 2007, the period we used for evaluation of ECHAM6 (2007-2010) could be affected by that. This would mainly affect the retrieval of the cloud phase due to an effect on the depolarization ratios by horizontally oriented crystals. As COSP does not use any information on the shape of ice crystals from the model (as most models do not have information on the shape of the ice crystals), the effect of horizontally oriented crystals can be ignored at least from the model side.

The authors note that ECHAM6 mixes too strongly in the Arctic and instead decide to turn to the models parameterization of the WBF process instead to attempt to remedy the bias in Arctic cloud cover. To this end, the authors increased the efficiency of the WBF process by decreasing the threshold of in-cloud ice water mixing ratio required to activate the depositional growth of ice. However, it appears that the authors are unaware that ECHAM6 (Lohmann and Neubauer(2018)), like many other climate models (Komurcu et al. (2014), Cesana et al.(2015), McCoy et al. (2016)), underestimates the proportion of liquid to ice in mixed-phase clouds. Decreasing the efficiency of the WBF process would only exacerbate this underestimate (Tan and Storelvmo (2016), Lohmann and Neubauer (2018)), which could also affect the climate sensitivity of the model (Tan et al. (2016), Lohmann and Neubauer (2018)).

Citing Lohmann and Neubauer (2018), the reviewer states that ECHAM6, like many other climate models, underestimates the proportion of liquid to ice in mixed-phase clouds. We would like to point out that Lohmann and Neubauer (2018) did not use the ECHAM6 Stevens et al. (2013), but used ECHAM6-HAM2 Zhang et al. (2012). Even though both models share a lot of their physical parameterizations, they significantly differ in the microphysical parametrizations. While ECHAM6 employs a single-moment scheme, ECHAM6-HAM2 uses a more sophisticated double-moment scheme. Even though both microphysical schemes stem from a common predecessor, they considerably vary in a lot of microphysical processes. One has therefore be careful when comparing ECHAM6-HAM2 to ECHAM6. Figure 3 in Lohmann and Neubauer (2018) shows the fraction of supercooled liquid clouds for ECHAM6-HAM2 (as well as for a number of sensitvity studies) on a global average. While on global average ECHAM6-HAM2 might underestimate this fraction, this figure does not show the fraction of supercooled liquid clouds in the Arctic. Komurcu et al. (2014) provides zonal-mean averages of supercooled liquid cloud fraction for different cloud top temperatures for ECHAM6-HAM2 (see their Figure 4) and for temperatures at or below -30° C, ECHAM6-HAM2 overestimates the amount of supercooled liquid clouds for high latitudes, even though by not much.
Figure 5 in Cesana et al. (2015) provides a similar zonal-mean, temperature binned supercooled liquid cloud fraction for MPI-ESM Giorgetta et al. (2013), which is the coupled version of ECHAM6, and a similar overestimation of supercooled liquid shows for MPI-ESM in the Arctic (compared to GOCCP at temperatures below -30° C). This overestimation of liquid cloud fraction in the lower part of the mixed-phase temperature regime is consistent with the fact that the overestimation of liquid cloud is only simulated in winter (DJF) and spring (MAM) where such cold temperatures can occur in high latitudes. Additionally, while being positively biased in high latitudes, MPI-ESM slightly underestimates the amount of supercooled liquid in the clouds in the mid-latitudes and in the tropics (see their Figure 6) even though not by much.

Thus, although the bias in cloud cover might be remedied, the partitioning of cloud phase would be further exacerbated. I would recommend the authors to look into how cloud thermodynamic phase is affected in the model before retuning the WBF process, which previous studies have already shown to be too efficient in climate models, including ECHAM6.

The reviewer is correct that even though the bias in liquid cloud fraction might be remedied by a stronger WBF processes, the effects of this measure on the actual (mass) phase partitioning (IWC/(LWC+IWC)) might be different. To this end, we follow the reviewer's advice and look into how cloud thermodynamical phase is affected before retuning the model. There is no observational product that can provide both, liquid and ice water content, on a large enough scale to compare it to a GCM. This is also the reason why all the studies cited by the reviewer are trying to mimic frequency ratio fraction of the cloud phase that can be provided by CALIOP. A possible approach to evaluate cloud phase would be to look at liquid/ice water path which can be derived from MODIS. As stated in the introduction, using passive spaceborne sensors might be problematic due to the environmental conditions and also due to fact the Arctic clouds are often mixed-phase clouds, which further complicates the retrieval of cloud microphysical properties (Khanal and Wang, 2018). To obtain at least a rough estimate of how the ice (mass) fraction is affected by a stronger by a stronger WBF process in ECHAM6, we added a plot of temperature-binned average ice fraction over the North Atlantic and over Siberia (Figure 6 in the revised manuscript). For the ice fraction in Siberia, we find quite low ice fraction ($\sim 70\%$) in the temperature range between -25° C and -10° C. Comparing this to in-situ observation of ice fraction as provided by Korolev et al. (2017) such a "plateau" is not visible. Figure 5-14 in Korolev et al. (2017) shows a more gradual increase in ice fraction (decrease in liquid fraction) with decreasing temperature (which can be seen in the bins for high/low ice fraction) and we think that the more or less constant ice fraction in the model over Siberia is another indication of an overestimated amount of liquid clouds over snow/ice covered surface as has been stated in the manuscript. As the ice fractions from in-situ observations and the ice fractions from the model are on a completely different spatial scale, one nevertheless has to be careful when doing such a comparison. As we have shown in our conclusion, the TOA shortwave CRE seems to be biased low in MPI-ESM which might be another hint that there is more liquid water in the clouds, which would make them less reflective, so we think that a slightly stronger efficiency of the WBF and therefore an higher ice (mass) fraction can be justified.

Why do the authors choose to focus on the WBF process? Why not ice nucleation for example, which also plays an important role in Arctic radiation (Prenni et al. (2007), Xie et al. (2013))?

The reason why we focused on the WBF is twofold. Firstly, it has to be a process that is able to efficiently reduce the amount of cloud liquid water. We conducted a number of sensitivity studies and modified the strength of all processes that can affect the liquid water content and we found the WBF to be by far the most efficient one. It also can be seen from table 4 and 5 in Klaus et al. 2012 that only the WBF process (γ_{thr}) and the collection of cloud droplets by snow (γ_4) are able to do so. Not included in this table is heterogeneous freezing of cloud droplets, but we found that increasing its efficiency did not lead to strong enough reduction in liquid cloud cover over snow and ice covered surfaces. Secondly, what makes it appealing to tune this process is the fact that it is strongly simplified in ECHAM6. Due to efficiency in tuning the amout of ice in clouds, modifying the strength of this process is also often used to tune the model to bring it into radiative balance. This can be seen from the fact that this parameter can vary up to an order of magnitude for different horizontal resolutions in ECHAM6. These considerations are now explained in more detail in the revised manuscript.

The authors note that although there were improvements to Arctic low liquid cloud cover by increasing the efficiency of the WBF process, total cloud fraction remained overestimated. To this end, the authors then modified the cloud cover scheme to allow for slight supersaturation with respect to ice in the model (their NEW experiments). The authors seem to point out in the main text that cloud although some of the high bias in low-cloud fraction is reduced in their NEW simulations, new low-biases in low-cloud cover are introduced. Although improvements to the high bias in low-cloud fraction were highlighted in the abstract and conclusions, they authors fail to mention that there appears to be a simultaneous introduction of a new low bias in low-cloud cover. In fact, this low bias in Arctic low-cloud fraction was already shown for the CAM5 model (Kay et al. (2016)), which allows for supersaturation with respect to ice (Gettelman et al. (2010)). Therefore, the author's parameterization does not seem to entirely solve the problem of the high bias in low-clouds in the Arctic, and the problem now reduces to an issue known to already exist in another model..

In the revised version of the manuscript, we try to more clearly point out why a temperature-weighted scheme for saturation vapor pressure in combination with an increased efficiency of the WBF process introduces an negative bias in low clouds. As the amount of low-level ice clouds remains more or less constant for different values of γ_{thr}, the amount of liquid clouds strongly decreases and therefore also the amount of clouds in general. The decrease in liquid clouds is mainly caused by the more efficient WBF processes which more efficiently turns liquid into ice clouds over continents compared to oceanic regions, it also affects clouds there. In the standard setup of ECHAM, liquid clouds are already biased low in those regions which is even further enhanced by a more effective WBF process. As liquid clouds seem to react rather sensitively to a more effective WBF process, only minor changes of γ_{thr} can have strong effects on the amount of liquid clouds and we think that setting γ_{thr} to $2.5 \cdot 10^{-6}\ \mathrm{kg\,m^{-3}}$ is already the best choice to improve WBF process. This value is the best compromise between improving cloud cover over snow and ice covered surfaces by simultaneously not further worsen clouds in other regions.

Also, although their temperature-weighted scheme for saturation vapor pressure may be new to the ECHAM6 model, it is not a new concept to climate models. Please cite previous work that have used similar weighting schemes in the calculation of saturation vapor pressure.

In the revised version of the manuscript, we now cite previous work that have used similar weighting schemes in the calculation of saturation vapour pressure.

Section 3: It seems to me that there is a chicken and egg game when using observations of the vertical profiles of temperature and humidity to establish a cause for high bias in low liquid clouds in the model. Low-clouds can in turn affect temperature and relative humidity, so how can one establish the cause for the low-cloud bias?

The reviewer is correct that no causal relationship can be established between a positive bias in low-level temperature and humidity and a positive cloud cover bias. Nevertheless, we believe that such biases in temperature and humidity can be an indicator of an overestimated cloud cover due to this two-way relationship that has been stated by the reviewer. We mainly used this comparison of vertical profiles to show that the reported cloud cover bias is not just due to possible uncertainties in GOCCP but is a real model problem. On request by the other reviewer, we additionally show data from ERA-Interim to also have information on temperature and humidity profiles on a wider spatial scale to show that there is a difference between snow/ice covered regions and water/open land. Looking at relative humidity, ECHAM6 seems to generally overestimate it over the continents, but this overestimation is most strongly pronounced in those regions we observed the strongest positive biases in low-level clouds, which make us confident that this overestimation actually exists.

Minor comments

Abstract, line 9: Phase partitioning" typically refers to mass ratio or frequency ratio defined as liquid/(liquid + ice) in mixed-phase clouds within a grid cell or specified domain. Here, the authors refer to the ratio of total low liquid cloud cover to total cloud cover. I recommend changing the terminology to avoid confusion.

We replaced "Improvements in the phase partitioning of Arctic low-level clouds" with "Improvements on the overestimated Arctic low-level liquid cloud cover"

I suggest changing the title of Section 2.1 to GOCCP" to reflect the fact that this CALIPSO-derived product was used in the analysis.

In the revised manuscript, we replaced all instances of CALIPSO with GOCCP and completely revised section describing GOCCP.

Page 2, lines 20-23: I would also mention the advantage that active satellites are also able to provide vertical profiles of clouds.

We mentioned that actives satellites can provide vertical profiles of clouds which cannot be provided by passive satellites.

Page 5, lines 10-13: If the mid-level cloud bias is similar to the low-cloud bias because of how low- and mid-level clouds are defined, then shouldnt that mean that the bias in mid-level clouds for JJA should resemble the bias for high clouds? It does not appear to.

We misinterpreted the similarity of the mid-level cloud bias to the low-cloud bias and our explanation does not hold. We therefore looked into the vertical profile of clouds and at the altitude of the threshold for low-, mid- and high-clouds (see attached figure). The thresholds themselves vary only a little between summer and winter. The actual cause for the seasonal variation of the mid-cloud bias can be attributed to the vertical position of the generally overestimated high-clouds in ECHAM6. The vertical extent of the troposphere is influenced by the atmospheric temperature which cause the cirrus clouds to be present at lower altitudes in winter. The similarity to low-cloud stems form the fact the temperatures are colder over snow and ice covered surfaces, which cause the cirrus clouds to be simulated at even lower altitudes and therefore contributed more the mid-level clouds compared to oceanic regions. We correct our false claim in the revised manuscript.

Page 5, line 20: This is an overstatement without formal proof. I would suggest replace is with appears to be.

Done.

Page 6, lines 19-22: This is an interesting hypothesis that may or may not be true. I would be more careful in emphasizing that the statement is speculative.

We try to more clearly formulate that this statement is speculative in the revised manuscript.

Page 8, line 13: Please add a reference for the WBF process and note the ways in which models simplify it (e.g. lack of dependence of vertical velocity). Please see Korolev (2007).

We added a reference for the WBF process at its first mentioning at the end of section 3. We also stated how ECHAM6 simplifies the WBF process due to its lack of dependence of vertical velocity.

Page 8, line 21: will" should go in front of depositional".

Done.

Page 10, Lines 11-12: Please specify that this the overestimate is with respect to GOCCP.

We now specify that the overestimation is with respect to GOCCP.

Page 11, lines 15-17: I disagree with this statement. The Karcher and Lohmann paper refers to cirrus clouds. In mixed-phase clouds, where liquid and ice clouds coexist and the WBF process occurs, the cloud may not necessarily glaciate immediately and will instead depend on how the liquid and ice are spatially distributed within the cloud (Tan and Storelvmo (2016)).

We removed the reference to the Karcher and Lohmann form our manuscript as it indeed refers more to cirrus clouds. Nevertheless, the way that mixed-phase clouds are parameterized in ECHAM6 will eventually cause any liquid water to be depleted quite quickly, as the condensation is the only process the can produce water in the mixed-phase temperature regime. As soon as there is enough cloud ice present and it exceeds γ_{thr}, condensation does not take place any more and any liquid water will quite quickly either freeze or evaporated. This can indeed be considered not physical as the presently used implementation of condensation/deposition does not allow for simultaneous growth of liquid and ice within a cloud. ECHAM6 also has no information on the subgrid distribution of liquid and ice within a cloud which might prevent this rather rapid depletion of liquid water.

Page 12, Line 17: reduce to" "reduce the"

Done.

Page 12, line 18: Please specify that supersaturation is with respect to ice.

We now specify that supersaturation is with respect to ice.

Figure 4: strength to strength

Done.

Figure 5: Please consider labelling the first value as the default value of the model in the legend of this figure for easy reference

Done.

Please remove all instances of the" in front of Arctic amplification".

Done.

References

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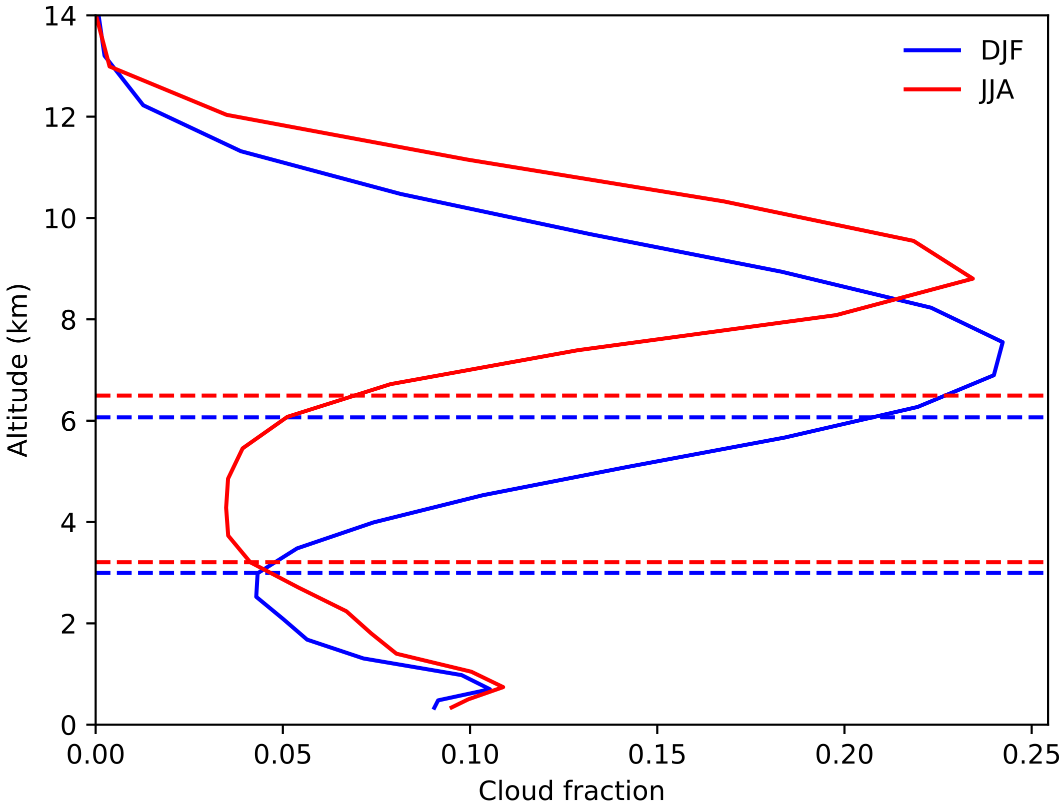

Figure 1: Vertical profiles of cloud cover for winter and summer in the Arctic as well as the thresholds for the low/mid/high classification.

Arctic cloud cover bias in ECHAM6 and its sensitivity to cloud microphysics and surface fluxes

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Abstract. Among the many different feedback mechanisms contributing to ~~the~~ Arctic Amplification, clouds play a very important role in the Arctic climate system through their cloud radiative effect. It is therefore important that climate models simulate basic cloud properties like cloud cover and cloud phase correctly. We compare results from the global atmospheric model ECHAM6 to observations from the ~~CALIPSO satellite active lidar instrument~~ CALIPSO-GOCCP using the COSP satellite simulator. Our results show that the model is able to reproduce the spatial distribution and cloud amount in the Arctic to some extent, but ~~that cloud cover has~~ a positive bias ~~(~~in cloud fraction is found in high latitudes, which is related to an overestimation of low- and high-level clouds. We mainly focus on the bias in low-level clouds and show that this bias is connected to surfaces that are covered with snow or ice and is mainly caused by an overestimation of liquid containing clouds. Slight improvements on the overestimated Arctic low-level ~~, liquid containing cloud) in regions where the surface is covered by snow or ice . We~~ liquid cloud cover could be achieved by a more effective Wegener-Bergeron-Findeisen (WBF) process but just revising this effectiveness of this process alone is not be sufficient to improve cloud phase on global scale as it also introduces a negative bias over oceanic regions in high latitudes. Additionally, this measure transformed the positive bias in low-level liquid clouds into a positive bias of low-level ice clouds keeping the amount of low-level clouds almost constant. By allowing for supersaturation with respect to ice, the amount of low-level ice clouds could also be reduced, even though the chosen temperature weighted scheme for saturation vapor pressure might be too efficient in removing those clouds in combination with a more effective WBF process. This emphasizes the need for a cloud cover parametrization that is explicitly designed to handle supersaturation with respect to ice and employs a more physical approach for saturation compared to our simple temperature weighted scheme. We additionally explored the sensitivity of low-level cloud cover to the strength of surface heat fluxes, ~~but only~~ and by increasing surface mixing, the observed cloud cover ~~bias cloud~~ and cloud phase bias cloud also be reduced. As ECHAM6 already mixes too strongly in the Arctic ~~, the cloud cover bias can mainly be attributed to cloud microphysical processes. Improvements in the phase partitioning of Arctic low-level clouds could be achieved by a more effective Wegener-Bergeron-Findeisen process but total cloud cover remained still overestimated. By allowing for a slight supersaturation with respect to ice within the cloud cover scheme, we were able to also reduce this positive cloud cover bias~~regions, it is questionable if one can physically justify to increase mixing even further.

1 Introduction

With temperatures rising nearly twice as strongly compared to the temperature increase of the Northern Hemisphere (Screen and Simmonds, 2010), the Arctic reacts especially susceptibly to global climate change. This is due to several positive feedback mechanisms that strengthen the warming in the high latitudes (Serreze and Barry, 2011). This ~~so called~~ so-called Arctic Amplification has important implications on the Arctic climate system like the extreme decrease in summer sea ice extent in recent years, the thawing of permafrost or the melting of glaciers in Greenland. Besides those effects on the regional scale, it is believed that ~~the~~ Arctic Amplification might have effects on the atmospheric circulation due to a decrease in the temperature gradient between mid and high latitudes (Francis and Vavrus, 2012). Additionally, the melting glaciers in Greenland contribute to the sea level rise, which will affect many coastal areas around the globe.

While globally having a cooling effect, clouds in the Arctic warm the surface most of the year except a short period in summer (Intrieri, 2002; Zygmuntowska et al., 2012; Kay and L'Ecuyer, 2013). As the amount of clouds is thought to increase in a warming Arctic (Liu et al., 2012), their positive cloud radiative effect (CRE) can further enhance Arctic Amplification. Using global climate models (GCMs) to assess the CRE in the Arctic on a larger scale is inevitable because of the complexity of the climate system in the Arctic. Due to this complexity, even present day estimations of the CRE from climate models in the Arctic are inconclusive (Karlsson and Svensson, 2013), as those models still struggle to correctly simulate even basic properties like cloud cover and cloud distribution (English et al., 2015; Boeke and Taylor, 2016), which complicates an assessment of future Arctic warming.

To improve the representation of clouds in climate models, it is important to compare their results to observations. Ground-based observations are usually fixed to a certain location and provide information on scales much smaller than those of GCMs. The difference in scales complicates the comparison of ground-based observations to simulations of climate models as those models cannot capture the small-scale heterogeneities present in observations. Another disadvantage of ground-based observations is that only a few sites in the Arctic conduct regular measurements of meteorological parameters, which also complicates a proper model evaluation. Nevertheless, those measurements provide valuable information on the climate in the Arctic and help to improve our understanding of many important processes in the Arctic climate system. An important tool often used in model evaluation is satellite remote sensing. Satellites can provide observations on spatial scales much closer to the scales of GCMs and are therefore well suited for assessing the performance of GCMs. Satellite remote sensing in the Arctic has to deal with several aspects that complicate their use in evaluating cloud properties in GCMs, which is especially the case for passive sensors. The polar night and often prevailing low-level inversions at high latitudes make it hard for passive instruments to discriminate between snow/sea ice and low-level clouds as they solely rely on the reflected and emitted radiation in the visible and thermal spectral ranges, respectively (Liu et al., 2010; Karlsson and Dybbroe, 2010). Active satellites like CloudSat (Stephens et al., 2002) and CALIPSO ~~(Winker et al., 2003)~~ (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations; Winker et al., 2003) are better suited, as they are less affected by the environmental conditions in the Arctic than passive sensors ~~(Kay and L'Ecuyer, 2013; Zygmunt~~
~~With their active radar and lidar, they have largely improved our understanding of clouds and aerosols in the climate system~~(Zygmuntowska
Additionally, active satellites can provide vertical profiles of cloud microphysical properties (especially CloudSat and to some

extend also CALIPSO) which passive satellites can not provide. To facilitate the comparison of properties derived by satellites and the output from GCMs, the Cloud Feedback Model Intercomparison Project's (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al., 2011) has been developed. With the help of this satellite simulator, it is possible to consistently evaluate the results from GCMs by using common definitions of clouds observed from satellite and clouds simulated in GCMs. COSP has been used in various model evaluation studies (Nam and Quaas, 2012; Cesana and Chepfer, 2013; Nam et al., 2014), with some studies especially focusing on clouds in the Arctic (Barton et al., 2012; English et al., 2014; Kay et al., 2016a). They show that some models have problems to correctly simulate the distribution and amount of clouds in the Arctic and also have problems to correctly simulate the phase state of clouds in high latitudes.

In the following, we will evaluate the performance of the atmospheric model ECHAM6 (Stevens et al., 2013) in the Arctic and will especially focus on the representation of clouds in this remote region. COSP is run online during the model integration. We will compare its output to ~~CALIPSO datasets~~ the GCM-Oriented CALIPSO Cloud Product (GOCCP) dataset (Chepfer et al., 2010), processed by the CFMIP Observations for Model Evaluation Project (CFMIP-OBS; Webb et al., 2017). Using ~~these datasets~~ this dataset ensures a consistent model-to-observation comparison as their diagnostics of observational data are consistent with the diagnostics within COSP.

2 Data and Model

2.1 ~~CALIPSO~~

~~CALIPSO was launched in April 2006 and is part of the A-Train. This constellation of satellites is flying in a polar, sun-synchronous orbit. Their orbit has an inclination of 98.2and the satellites cross the ascending/descending node at 1330/0130 local solar time. Due to their inclination and due to the fact that only a narrow swath at nadir is observed, the satellites can only retrieve information from 82N to 82S. It takes 16 days for the satellite to sample again the same swath. The fact that there is no information available north of 82N is disadvantageous for our study, but in return, all regions close to the northern boundary of 82N are sampled with a high temporal frequency due to the inclination of the orbit.The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations satellite (CALIPSO Winker et al., 2003) hosts a lidar that provides high resolution profiles of clouds and aerosols. This lidar - the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) - is a two wavelength (1064 nm, 532 nm), near-nadir looking lidar. Both channels are used to measure the lidar backscattering intensity. Comparing the backscattered intensity to that of a molecular atmosphere (no clouds or aerosols) gives the lidar scattering ratio. To further retrieve information on the properties of the particles (size, shape, type) that scatter the emitted light back to the sensor, CALIPSO has two receivers for the backscattered light at 532 nm that measure the two orthogonally polarized components of the backscattered lidar signal. We use CALIPSO data from the GCM-Oriented CALIPSO Cloud Product (GOCCP) dataset (Chepfer et al., 2010), which is generated from CALIOP Level 1B NASA Langley Atmospheric Sciences Data Center CALIPSO datasets. The gridded data from CALIPSO-GOCCP (hereafter referred to as CALIPSO data) is available on a 2× 2grid and is consistent with the data generated by CALIPSO simulator within COSP as it uses the same cloud detection thresholds. In this study, we will evaluate cloud cover derived from CALIPSO in different altitudes bands (low, mid,~~

~~high clouds), which are defined as follows: high clouds $p_{top} < 440$ hPa mid clouds 680 hPa $> p_{top} \geq 440$ hPa low clouds $p_{top} \geq 680$ hPa The GOCCP product defines a cloud detection for scattering ratios larger than 5. Due to the ability of the satellite to retrieve information on the polarization of the signal, it is further possible to discriminate the phase state of the clouds seen by the lidar.~~

2.1 ECHAM6 and COSP

In this study, we use the atmospheric model ECHAM6 (Stevens et al., 2013), developed by the MPI in Hamburg in its most recent version (ECHAM6.3). In all our simulation, the model is run at a resolution of T63, which is equivalent to a Gaussian grid of approximately $1.875° \times 1.875°$. In the vertical, we use a resolution of 47 levels. The model's vorticity and divergence are nudged to ERA-Interim reanalysis data (Dee et al., 2011) to enable comparison to satellite observations despite the relatively short run time of the model of less than 5 years. We use monthly observations of sea surface temperature and sea ice concentration from the AMIP II dataset (Taylor et al., 2000) as boundary conditions to further constrain the model.

To better compare the model results to the satellite observations, we use ~~the Cloud Feedback Model Intercomparison Project's Observation Simulator Package (COSP; Bodas-Salcedo et al., 2011)~~COSP (Bodas-Salcedo et al., 2011), version 1.4. Multiple satellite simulators are available within COSP, but here, only the simulator for ~~CALIPSO~~ CALIPSO-GOCCP (ActSim; Chepfer et al., 2008) is used. COSP uses model output like the profiles of temperature, pressure, cloud fraction, cloud water content, cloud particle concentration, as well as precipitation flux of rain and snow from large-scale/convective precipitation as an input for its calculations. To ~~account for subgrid scale variability of the cloud cover~~enable a more consistent comparison between model and observed cloud properties, COSP divides each ~~model~~ grid box into a specified number of subcolumns (here we use 40 subcolumns) ~~that have a hydrometeor (cloud) fraction of either 1 or 0, so that the average over all subcolumns is equal to~~ to account for subgrid scale variability of grid-scale hydrometeor properties (i.e. cloud and precipitation). For the subdivision of cloud properties into subcolumns, the ~~hydrometeor (cloud) fraction of the model grid box~~Subgrid Cloud Overlap Profile Sampler (SCOPS) is used within the framework of COSP, that was originally developed as part of the ISCCP simulator (Klein and Jakob, 1999; Webb et al., 2001). It applies a pseudo-random sampling of cloud properties to be consistent with the cloud overlap assumption of the host model. Additionally, the precipitation fluxes in those newly created subcolumns are determined following a simple algorithm developed by Zhang et al. (2010). The calculations of the satellite simulators within COSP are then performed on each subcolumn to simulate specific signals received by instrument and to mimic the retrievals derived from these instruments. By using the same instruments sensitivities and cloud overlap assumptions as used in ~~the CFMIP-OBS dataset~~GOCCP, COSP generates an output that is similar to the observations from satellites and also provides a common basis for comparing results from different climate models. The satellite simulator is implemented into ECHAM6 and is run online during the integration of the model. The output fields of COSP are interpolated on the $2° \times 2°$ ~~CFMIP-OBS~~ GOCCP grid for better comparison. For the evaluation of ECHAM6 in section 3, we run the model from 2007 to 2010, while for the sensitivity studies in section 4 we only run it for 2007 and 2008 to reduce computational cost.

3 ~~Arctic clouds and profiles of temperature and humidity in ECHAM6~~

~~In the following, we evaluate the temporal mean of a nudged~~

2.1 GOCCP

To evaluate to what extent ECHAM6 ~~run for the years spanning 2007 to 2011 with prescribed sea surface temperatures and sea ice concentration and a spin-up of 6 months. The top row of shows the multi-year average distribution and amount of the total cloud cover for CALIPSO and~~ is able to simulate cloud marco- (cloud cover) and microphysical (cloud phase) properties of Arctic clouds, we use the GCM-Oriented CALIPSO Cloud Product (GOCCP) dataset (Chepfer et al., 2010), which is generated from the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) Level 1B NASA Langley Atmospheric Sciences Data Center CALIPSO datasets. The CALIPO data in the GOCCP dataset is interpolated onto a $2° \times 2°$ grid in the horizontal and on a equally spaced vertical grid (Δz=480 m) with 40 vertical levels ranging from the surface to 19 km. On this grid, the lidar scattering ratio (SR) is computed by comparing the backscattered intensity of the lidar beam to that of a molecular atmosphere (no clouds or aerosols). A layer can then be classified as cloudy ($SR > 5$), clear ($0.01 < SR < 1.2$), fully attenuated ($SR < 0.01$) or unclassified ($1.2 < SR < 5$). Using these thresholds, cloud cover for different layers (low, mid, high) can be diagnosed. Those layers are defined as follows:

high clouds		p_{top}	≤ 440 hPa
mid clouds	680 hPa $>$	p_{top}	≥ 440 hPa
low clouds		p_{top}	≥ 680 hPa

Furthermore, the GOCCP dataset contains information on the phase of the cloud that is observed by CALIOP. By comparing the total backscattered lidar signal (ATB) to the perpendicularly (relative to the incident laser light) polarized backscattered lidar signal ($ATB_\perp$), information on the shape of the particle that scattered the lidar beam can be retrieved. Assuming a scattering angle of 180° and no multiple scattering, a spherical particle does not change $ATB_\perp$ while a nonspherical particle polarizes the backscattered lidar signal and consequently leads to a larger $ATB_\perp$ (Cesana and Chepfer, 2013). Using a phase discrimination line that is a function of ATB and $ATB_\perp$ (see Equation 3 in Cesana and Chepfer, 2013), one can distinguish in which phase state the scattering particle is. In late 2007, the nadir pointing angle of CALIPSO has changed to avoid spurious values of optical properties in case of oriented crystals being present in clouds. This might have affect our comparison, but we could not find any information on how the change in the viewing geometry might have affected the GOCCP dataset.

Even though an active sensor like CALIPSO is better suited for Arctic spaceborne remote sensing than passive sensors (Zygmuntowska et al., 2012; Kay and L'Ecuyer, 2013), it will also be affected by the atmospheric conditions at high latitudes, which will introduce observational uncertainties. Due to the prevailing low-level, liquid containing clouds in the Arctic (Shupe and Intrieri, 2004), the lidar beam can get attenuated by those optically thick clouds (Cesana et al., 2012). The lidar beam can not penetrate through those low-level clouds and will cause an underestimation of clouds in the lowest layers of the atmosphere. Comparing several CALIPSO-dervied datasets to ground based observations in Barrow and Eureka, Liu et al. (2017) showed that near surface cloud cover can be underestimate by up to 40 % due to the attenuation of the lidar beam by those opaque, low-level, liquid containing clouds. Even if the lidar beam is not attenuated and can reach down to the surface, clouds might be missed by GOCCP. As Lacour et al. (2017) stated, using a SR > 5 to detect clouds can cause a significant underestimation of low-level ice clouds because those optically thin clouds with small vertical extent might be missed with such a high detection threshold. Nevertheless, they found that the GOCCP dataset is superior over most passive spaceborne sensors as it is much closer the ground based observations. Further uncertainty is introduced by different spatio-temporal sampling when comparing ground based observation to spaceborne observation (Cesana et al., 2012; Liu et al., 2017).

To circumvent some of the reported issues, we not directly compare the modeled cloud cover to GOCCP but make use of COSP. By using the same detection threshold for clouds, not suffering from similar attenuation effects of the (simulated) lidar beam and also comparing the modeled and observed clouds on a similar spatial and temporal scale should enable a more consistent comparison. To show that the COSP-derived cloud cover from ECHAM6 suffers from a similar underestimation of low-level cloud cover, we compare modeled (ECHAM+COSP ~~output. The bottom row shows the difference from the CALIPSO observations. The black contour line indicates the extent of the snow/sea ice cover . An area is classified as covered with snow and ice if the average snow depth in the grid box is thicker than 2 cm or the sea ice fraction within a gridbox is greater than 50~~minus ECHAM) to observed (GOCCP minus ground based observations) cloud cover profiles in Figure 1. For ground based observations, we use data from the 35-GHz millimeter cloud radars (MMCR) in Barrow and Eureka as described in Shupe et al. (2011) for the period from 2007 to 2009. Similar to Liu et al. (2017), GOCCP underestimates the cloud amount in lowest levels of the troposphere by 15 to 20 ~~%~~% at both locations for reasons described above. Looking at the difference between COSP- and ECHAM-derived (with that we mean cloud cover as diagnosed by the cloud cover scheme in ECHAM6), we see that ECHAM+COSP also omits clouds close to the surface. Looking at the observed and modeled differences of the cloud cover profiles, we find that the differences almost perfectly match for Barrow (except for the lowest level which might be an artifact of vertically interpolating the data on the ECHAM6 grid). Differences at Eureka also show an underestimation of cloud cover close to the surface, even if the difference of observed to modeled clouds does not compare as well as for Barrow. Nevertheless, the comparison shown in Figure 1 make us confident that the observational uncertainties present in the CALIPSO derived GOCCP dataset can in part be countered by using COSP derived cloud products, which enables a fair comparison between observed and model clouds (Kay et al., 2016b).

3 Arctic clouds in ECHAM6

In the following, we evaluate the temporal mean of a nudged ECHAM6 run for the years spanning 2007 to 2011 with prescribed sea surface temperatures and sea ice concentration. For this comparison, we use monthly averaged GOCCP data for the same period that contain both daytime and nighttime overpasses. ECHAM6 + COSP is able to reproduce the general cloud amount and distribution as observed by ~~CALIPSO~~ GOCCP to some extent, but is biased high over the Arctic Ocean, Siberia and over the northern parts of Canada. Those areas correspond to areas that are covered with snow and sea ice, respectively. The overestimation of cloud cover in those areas is opposing the general low bias in cloud cover over the ocean and continental regions that are not covered by snow which might be due to the fact that ECHAM6 generally seems to simulate too few clouds at low and mid levels (Stevens et al., 2013).

To explore what causes the positive bias in cloud amount over snow and sea ice covered areas, it is important to know at which altitude the clouds are situated and of which thermodynamic phase (liquid or ice) they are composed. Figure 3 shows the meridional mean difference of ECHAM6 + COSP and CALISPO from 60°N to 82°N. Besides the difference in total cloud cover, Figure 3 also shows the difference in low, mid and high cloud cover (altitude bins defined as in subsection 2.1) as well as the difference in total liquid and total ice cloud cover. As low clouds are the most common cloud type in high latitudes, the difference in total cloud cover is strongly influenced by the difference of low-level clouds. For those low-level clouds, a clear influence of season and longitude on the difference in cloud cover can be observed, which is especially the case in winter and spring. During these two seasons and over nearly all regions (except the Atlantic Ocean), ECHAM6 + COSP simulates a ~~higher cloud cover~~ greater cloud fraction than observed by ~~CALIPSO~~GOCCP. As seen in Figure 2, there seems to be a connection between the snow/sea ~~-~~ice coverage of the surface which can also be observed in Figure 3. ~~In contrast to~~ Besides low-level clouds, high-level clouds ~~show no real~~ also seem to be not simulated correctly in ECHAM6. The model generally overestimates the amount of high-level clouds, but in contrast to low-level clouds, they do not really show a dependency on longitude and only a weak dependency on the season~~and their amount is generally overestimated~~. For mid-level clouds, cloud cover almost perfectly matches the observations in spring and fall~~–~~, whereas in summer~~,~~ /winter, mid-level cloud cover is underestimated/overestimated by the model. For ~~all three seasons,~~ spring, summer and fall no significant dependency on longitude is distinguishable ~~. This is different for winter , where the longitudinal behavior of the cloud cover bias is similar to that of~~ which is not the case for winter where a similar can be observed as for low-level clouds. ~~A possible explanation for this bias in~~ The reason for seasonal variation of mid-level clouds is ~~that clouds that are considered to be low-level clouds in all other season are partly being accounted for as~~ caused by the varying height of the troposphere, which is dependent on the tropospheric temperature profile. For colder temperatures, the tropopause is much lower than for warmer temperatures which causes cirrus clouds to vary in altitude. Therefore, some of the cirrus clouds in ECHAM6 are considered mid-level clouds ~~due to the fact that the geopotential height of the 680 hPa pressure surface is lower during winter because of the colder temperatures of the atmosphere~~in winter which is not the case for GOCCP. This effect reveres in summer, when ECHAM6 underestimates the amount of mid-level clouds when ECHAM6 simulates the bulk of the cirrus clouds at higher altitudes. When further discriminating between ice- and liquid-containing clouds (bottom row in Figure 3), one finds that this seasonal variation with a too large cloud cover in winter and spring mainly stems from an overestimation of liquid-containing clouds that usually can be found in the lower troposphere. In the Arctic, liquid containing clouds are of special importance as those clouds strongly influence the radiative budget at the surface due to their large optical thickness and strong effect on net surface longwave radiation (Shupe and Intrieri, 2004) which causes a warming at the surface. For ice clouds, on the other hand, only very little seasonal or longitudinal variability in the deviation is distinguishable, and it is comparable to the difference in high cloud cover as those high clouds mainly consist of ice particles. Taken together, ECHAM6 simulates low-level, liquid containing clouds too frequently, and this overestimation ~~is~~ appears to be connected to properties of the underlying surface. Additionally, high-level clouds are also overestimated, but this should not be subject of this study.

~~To investigate what might be a cause for the overestimation~~ To show that the above reported overestimated amount of low-level

~~, liquid-containing clouds in ECHAM6, we next~~ clouds is not just due to possible observational uncertainties in the GOCCP, we additionally assess how well the model is able to reproduce profiles of temperature and humidity in the Arctic. We therefore compare profiles of temperature and humidity from the model to profiles measured by radiosondes within high latitudes. Additionally, we used data from ERA-Interim (Dee et al., 2011) to obtain further information about the stratification besides the spatially limited profiles from radiosondes. Due to the sparse availability of observational data in high latitude, one should not take data from ERA-Interim at face value, but it should nevertheless a rough estimate to evaluate ECHAM6. To make the profiles of the various stations independent of surface elevation, we use height above the ground as the vertical coordinate in our analysis and linearly interpolate the radiosonde data to altitudes above the surface spanning from 0 m to ~~3000~~1000 m in steps of 500 m. Using such a vertical coordinate facilitates the comparison of several stations that might vary in surface elevation. Additionally, it is independent of synoptic situation which would not be the case if one uses pressure as the vertical coordinate. A disadvantage of this vertical coordinate is that the surface elevation in the model and the reanalysis is a grid-box mean which can deviate from the actual surface elevation of the station~~but as~~. As most stations are situated near the coast or within the rather flat plains of the Siberian tundra, we expect only minor inconsistencies. One also has to keep in mind that the vertical resolution of the soundings~~and~~, ECHAM6 and ERA-Interim is rather poor, so only a certain level of detail can be expected from them. ~~Nevertheless, they provide a useful estimate of the vertical stratification of~~ Even though an evaluation of several reanalysis datasets in the Arctic have shown that ERA-Interim should be well suited (Lindsay et al., 2014), one should not take the data from ERA-Interim at face value due to the sparse availability of observations in high latitudes that can be used to constrain the the ~~atmosphere.~~ reanalysis. Figure 4 shows that ~~the model overestimates temperatures below~~ ECHAM6 underestimates surface temperature compared to ERA-Interim in large part of high latitudes. In contrast, radiosonde data shows a slight positive bias, especially over Siberia. This discrepancy between ERA-Interim and the radiosondes is not as large at 500 m and 1000 ~~m above ground level, while it simulates lower temperatures than measured by the radiosondes above this level. Especially at the surface, temperatures in~~ m AGL. At those altitudes, ECHAM6 ~~are more than 1 K higher than observed. This positive temperature bias close to the surface might be related to~~ is in good agreement with the ~~overestimation of low-level clouds as they exert a warming effect on the surface. The overestimated cloud cover can also be seen in the difference of absolute humidity as it is always higher than observed by the radiosondes. As the absolute humidity is limited by saturation humidity, and therefore decreases with decreasing temperature will also cause the differences to become smaller, so we also add the difference~~ observations and ERA-Interim. Looking at the biases in relative humidity~~as it is temperature-independent. To ensure comparability, relative humidity from the observations and the model is always calculated with respect to saturation pressure over water~~, both ERA-Interim and the radiosonde profiles show that ECHAM6 seems to overestimate relative humidity at the surface. This overestimation is most strongly pronounced over Siberia and northern America. This is ~~necessary as relative humidity in the model output can either be calculated with respect to water or with respect to ice, depending on the atmospheric condition (for more information. see). As for the difference of absolute humidity, the difference in relative humidity between the model and the soundings is larger close to the surface (~20 %)but decreases quite rapidly and is more or less constant at 7% above 1000 m and remains positive throughout the lower troposphere. In general, the moisture content of the atmosphere can either be influenced by advection or local fluxes of moisture out of and into the atmosphere. As~~ consistent with the overestimated low-level cloud cover in those regions as shown in Figure 3. Even though no direct causal relationship can be derived that a positively biased relative humidity is responsible for the positive bias in cloud cover (as both can influence each other), a positive bias in relative humidity nevertheless indicates that also cloud cover in those regions might be overestimated. At higher altitudes, the positive bias in ~~humidity is connected to snow and ice coverage of the surface, it is plausible that local effects are the cause for the observed bias.~~ relative humidity becomes smaller and also only little regional variation can be observed. This indicates that the low-level cloud cover bias is caused by clouds that are situated close to the surface.

The cloud cover and moisture bias ~~therefore~~ implies that either the removal of atmospheric moisture by precipitation or fluxes of moisture from the surface into the atmosphere are not represented correctly in the model and that this seems to be connected to the underlying surface. Moisture fluxes into the atmosphere are directly influenced by surface properties like surface roughness (which can be reduced by snow on the surface) or availability of humidity at the surface (which itself is a function of temperature) and indirectly through increased stability of the layers close to the surface that consequently has an influence on vertical mixing of momentum and latent/sensible heat fluxes. The linkage between surface properties and moisture removal can be established through the modification of the atmospheric stratification ~~that consequently influences cloud microphysical processes. Over snow and ice covered surfaces,~~ as the strong radiative cooling causes the temperatures to be significantly lower compared to a snow- and ice-free surface~~which may cause temperature-dependent~~. Possibly, temperature dependent processes like the Wegener-Bergeron-Findeisen ~~(WBF) process~~ process (Wegener, 1911; Bergeron, 1935; Findeisen, 1938) or the heterogeneous freezing ~~of cloud~~ might not sufficiently turn liquid water into ice ~~to be more effective. As most precipitation in higher latitudes is formed via the ice phase, a higher ice content can lead to the dissipation of clouds, as can be seen in the rather rapid transition from the cloudy into the clear state that is often observed in the Arctic (Morrison et al., 2011)~~in those regions, which we will investigate in the following section.

4 Sensitivity studies

In this section, we will examine how sensitively cloud cover ~~reacts to modified surface heat fluxes and~~ and cloud phase react to modifications of cloud microphysical parametrization ~~. As the cloud bias is related to snow and ice covered surfaces, it is possible that fluxes of moisture from the surface into the atmosphere are not represented correctly in the model. In ECHAM6, turbulent surface fluxes of either heat ($\psi = h$) or momentum ($\psi = m$) are described using the following bulk-exchange formula:~~

$$\cancel{\overline{w'\psi'} = -C_\psi \, |\boldsymbol{V}| \, (\psi_{\mathrm{nlev}} - \psi_{\mathrm{sfc}}),}$$

~~where C_ψ is the bulk exchange coefficient with respect to ψ, $|\boldsymbol{V}|$ is the difference of the absolute wind velocity at the surface and the wind velocity in the lowest model level and the last term in parentheses is the difference of the respective quantity between the first model level (ψ_{nlev}) and at the surface (ψ_{sfc}). C_ψ can be further separated into the product of a neutral limit transfer coefficient $C_{\mathrm{N},\psi}$ (which only depends on surface properties like surface roughness and the height of the first model~~

~~level) and a (surface-layer) stability function f_ψ:~~

$$C_\psi = C_{\mathrm{N},\psi}\, f_\psi$$

~~Those stability functions can be derived from Monin-Obukhov similarity theory by integrating the flux-profile relationships from the surface up to the lowest model layer but this is not practical for climate models. Therefore, ECHAM6 uses empirical expressions for those stability functions similar to the ones proposed by Louis (1979), depending on both surface properties and stability of the layer between the surface and the lowest model level (expressed by the moist Richardson number). To obtain a first impression on how cloud cover reacts to increased/decreased surface fluxes, we introduced a scaling factor μ into so that it becomes:~~

$$C_\psi = \mu\, C_{\mathrm{N},\psi}\, f_\psi.$$

~~This scaling factor can be used to increase or decrease the neutral limit transfer coefficient which can be interpreted as a modification of the surface roughness, where values of μ greater than 1 denote higher surface roughness and stronger mixing, while values of μ less than 1 denote lower surface roughness and reduced mixing, respectively. We only modify this scaling factor for snow and sea ice covered surfaces and set it to 1 elsewhere. As before, a surface is considered snow-covered when snow height is higher than an arbitrarily chosen value of 2 cm and, a surface is considered sea ice covered if more than 50 % a grid box is covered by sea ice. In we show the effect of increasing ($\mu = 5$) and decreasing ($\mu = 0.2$) mixing on low cloud cover over those surfaces in the northern hemisphere (for comparison we also added CALIPSO cloud cover). For sea ice covered surfaces, increased mixing ($\mu = 5$) leads to reduced total cloud cover during winter and spring, while in summer it leads to an increase in cloud cover compared to base run ($\mu = 1$). For decreased mixing ($\mu = 0.2$), exactly the opposite is simulated, with more clouds in winter and few clouds during summer compared to the base run. Even if the cloud cover bias is reduced in the runs with increased mixing, the modeled cloud cover is still higher compared to CALISPO during winter, while only minor changes in the cloud cover bias are found for summer. Total cloud cover behaves similarly for increased/decreased mixing whenever a grid box is snow covered (no information is available during summer as no grid box is snow-covered), and cloud cover is also overestimated for all runs during winter compared to CALIPSO. In general, increased mixing is expected to increase the moisture fluxes from the surface into the atmosphere and therefore to increase the moisture availability in the lowest levels of the atmosphere. While this assumption is valid for most parts of the globe, heat fluxes in the Arctic can reverse during winter so that fluxes of sensible and latent heat from the lowest layers of the atmosphere are directed towards the surface. This is due to the often observed low-level temperature inversion that also leads to qualitatively similar moisture profiles as saturation water vapor content is a function of temperature. In case of such a moisture inversion, increased mixing increases the latent heat fluxes from the atmosphere onto the surface, and this process is a sink for atmospheric moisture. In case of a temperature inversion, stronger mixing causes surface temperatures to increase, but the effect of this temperature increase on cloud cover is twofold. On the one hand, warmer surface temperatures make the atmospheric stratification less stable, which further increases mixing and consequently leads to stronger removal of atmospheric moisture by latent heat fluxesas long as the moisture inversion is still present. On the other hand, a warmer surface increases the moisture content. Consequently,~~

~~the vertical moisture gradient is weakened, also resulting in weaker moisture fluxes from the atmosphere onto the surface according to . Altogether, the increased moisture removal seems to dominate over the decrease in vertical moisture gradient, as cloud cover is reduced due to stronger mixing. Despite the potential to improve cloud cover by stronger surface mixing over snow and ice covered surfaces, it is questionable whether one can physically justify to further increase mixing as most climate models already mix too strongly in stable boundary layers (Holtslag et al., 2013). We will further elaborate on that in the next section. Besides the rather straightforward influence of surface properties on surface mixing strength, misrepresented cloud microphysical processes also affect cloud cover in the Arctic~~and to modified surface heat fluxes. As we have shown in the previous section, it is mainly the low-level, liquid containing clouds that cause ~~this observed cloud cover bias~~ the low clouds bias in ECAHM6. Low-level clouds in the Arctic are typically mixed-phase clouds, so the overestimation of liquid clouds can be related to a misrepresentation of microphysical processes that act in this temperature regime, i.e., heterogeneous freezing of cloud liquid into ice or the production of cloud ice at the expense of cloud liquid water, also known as the Wegener-Bergeron-Findeisen ~~process. In this study, we will focus primarily on the WBF processas it is an effective way of turning liquid into ice clouds by making the depositional growth of ice crystals more efficient~~(WBF) process. As most precipitation in higher latitudes is formed by the aforementioned process, a higher ice content should lead to the dissipation of clouds, as can be seen in the rather rapid transition from the cloudy into the clear state that is often observed in the Arctic (Morrison et al., 2011). Previously, Klaus et al. (2012) explored the sensitivity of cloud microphysical properties in a single column setup of the regional Arctic climate model HIRHAM5, which also uses the physical parametrizations of ECHAM. They modified several commonly used microphysical tuning parameters and only a stronger WBF process and a more effective collection of cloud droplets by snow were able to reduce the liquid water content. Additionally, we conducted a sensitivity study to explore the effect of an increased efficiency of heterogeneous freezing of cloud droplets, which also reduced the liquid water content. Out of the three processes, the WBF process was by far the most efficient in turning cloud liquid into cloud ice and was also used by Klaus et al. (2016) to tune the microphysics in HIRHAM5, who reported a similar overestimated amount of liquid clouds. In our study, we will therefore explore the effect of different strengths of the WBF process on cloud cover and cloud phase. Depositional growth of cloud ice takes place, according to the ECHAM6 parameterizations, if one of the following conditions is met:

1. $T < -35°$ C
2. $T < 0°$ C and $x_i > \gamma_{\text{thr}}$ (where ~~x_i~~ x_i is the in-cloud ice ~~water mass~~ mixing ratio)

The second conditions can be seen as a simple parametrization of the WBF process, as it allows ~~condensation of liquid water~~ deposition/condensation of ice/liquid to take place for temperatures below 0° C if the ice ~~water~~ mixing ratio within the cloud is above/below a certain value. ~~Setting an in-cloud ice water mixing ratio threshold is a reasonable~~ In ECHAM6 and other climate models, the WBF process is often strongly simplified. As can be seen from the condition for the onset of the WBF process in ECHAM6, there is no explicit dependence of this process on vertical velocity. Korolev and Mazin (2003) have shown that only if the updraft speed u_z within a cloud ~~. Only after a sufficiently large number of crystals is formed by freezing, depositional growth of ice crystals will efficiently~~ is less than a threshold vertical velocity u_z^*, the WBF process can deplete any excess water vapor at the expense of liquid water within the cloud. u_z^* is defined as follows:

$$u_z^* = \frac{e_s - e_i}{e_i}\,\eta\,N_i\,\bar{r}_i \tag{1}$$

where e_s/e_i is the saturation vapor pressure over liquid/ice, η a coefficient dependent on temperature and pressure, N_i the ice crystal number concentration and $\bar{r}_i$ the mean radius of the ice crystals. Assuming $\frac{e_s-e_i}{e_i}\eta$ to be constant, u_z^* and therefore the condition for the onset of the WBF process (for a given u_z and a given temperature) is only function of $N_i\,\bar{r}_i$. As ECHAM6 uses a single moment microphysical scheme, only information on the ice mixing ratio is present. As the ice mixing ratio also can be calculated as a function of N_i and ~~supersaturation with respect to ice will relax back to unity (Kärcher and Lohmann, 2003). In the standard setup, $\gamma_{\rm thr}$ is set to $5\cdot10^{-6}$ kg m^{-3}, but this tuning parameter~~ $\bar{r}_i$ might at least partly justify the use of $\gamma_{\rm thr}$ as a threshold for the onset of the WBF. Nevertheless, this is quite an strong simplification for the onset of this process as it is now independent on vertical velocity. This also reflects on the fact that $\gamma_{\rm thr}$ is resolution-dependent in ECHAM6 and can vary by an order of magnitude between the different horizontal resolutions of ECHAM6. ~~We will evaluate how a reduction affects the total amount and the partitioning between liquid and ice~~

Due to this strong variation of $\gamma_{\rm thr}$ for different horizontal resolutions and due to the fact that it is one of the few parameters that is able to reduce the liquid water content of clouds in the ~~model~~Arctic (Klaus et al., 2012), we will now explore how sensitive cloud cover and cloud phase reacts to change in $\gamma_{\rm thr}$. Lower values of $\gamma_{\rm thr}$ increase the effectiveness of the WBF process, leading to less cloud water but more cloud ice to be present. As almost all precipitation in the Arctic is formed via the ice phase, a decrease of $\gamma_{\rm thr}$ is expected to eventually lead to a decrease in cloud cover as cloud condensate should be more efficiently removed via precipitation. As can be seen from Figure 5, decreasing $\gamma_{\rm thr}$ in fact leads to a reduction in low-level liquid-phased clouds ~~winter, but the positive bias~~ in winter. It also can be seen that liquid cloud fraction decreases quite strongly if one halves the $\gamma_{\rm thr}$ and that this decrease is more effective over continental regions compared to oceanic regions. Despite this fact, tuning low-level liquid cloud cover to match the observed liquid cloud cover of GOCCP using the WBF process alone poses difficulties. Setting $\gamma_{\rm thr}$ to $2.5\cdot10^{-6}$ kg m^{-3} or lower improves low-level liquid cloud cover east of 90° E, but introduces and further strengthens an already observable low bias in low-level, liquid clouds between 315° E and 90° E in ECHAM6. This implies that tuning the WBF can not be used to tune the cloud microphysics alone. Due to the fact that other processes that are able to reduce the liquid water content (more effective collection of cloud droplets by snow and heterogeneous freezing) do not do this in a sufficiently strong manor, we nevertheless think that increasing the efficiency of the WBF process is the most promising approach to tune Arctic cloud phase.

In the evaluation of cloud phase in section 3, the cloud phase ratio is used, which only can provide information of cloud phase as long as the lidar beam is not attenuated. This might cause some clouds to be missed in GOCCP and also in COSP, especially if clouds contain water. Therefore, we will look at the mass phase ratio as it is simulated by the model directly so that phase ratio is not affected by the attenuation of the lidar beam. To estimate how ice mass fraction is simulated in ECHAM6, we look at temperature-binned ice fraction in the North Atlantic and Siberia and how ice fraction changes for lower values of $\gamma_{\rm thr}$ in ~~total~~ Figure 6. For the North Atlantic, clouds mostly consist of ice up to a temperature of $-10°$ in the default setting of $\gamma_{\rm thr}$ before clouds start to become more liquid. The ice fraction in Siberia already decreases at colder temperature and then stays more or less constant at a value of 0.7 up until $-5°$. Comparing this to in-situ observation of ice fraction as provided by Korolev et al. (2017) such a "plateau" is not visible. Figure 5-14 in Korolev et al. (2017) shows a more gradual increase in ice fraction with decreasing temperature (which can be seen in the bins for high/low ice fraction) and we think that the more or less constant ice fraction in the model over Siberia is another indication of an overestimated amount of liquid clouds over snow/ice covered surface as has been shown in Figure 3. As the ice fractions from in-situ observations and the ice fractions from the model are on a completely different spatial scale, one nevertheless has to be careful when doing such a comparison. To our knowledge, there is no observational product available that can provide liquid water and ice water content on a global scale. A possible approach to evaluate cloud phase would be to look at liquid/ice water path which can be derived from MODIS. As stated in the introduction, using passive spaceborne sensors might be problematic due to the environmental conditions and also due to fact the Arctic clouds are often mixed-phase clouds, which further complicates the retrieval of cloud microphysical properties (Khanal and Wang, 2018). Decreasing γ_{thr} has quite a strong effect on the ice fraction over Siberia where ice fraction is increased and the general shape of the curves over the North Atlantic and over Siberia are now quite similiar to each other. While a higher value of γ_{thr} might be able to remedy the bias of liquid cloud over snow and ice covered surfaces, a too high value of γ_{thr} will lead to an underestimation of liquid clouds over open water. As liquid clouds react rather sensitively to a more effective WBF process, only minor changes of γ_{thr} can have strong effects on the amount of liquid clouds and we think that setting γ_{thr} to $2.5 \cdot 10^{-6}\ \mathrm{kg\,m^{-3}}$ is the best choice to revise the WBF process. This value is a good compromise between improving cloud cover/phase over snow and ice covered surfaces by simultaneously not further worsen clouds in other regions.

Even though a more effective WBF is able to reduce low-level liquid cloud cover, the overall low-level cloud cover remains more or less unchanged. This is striking, as one would expect cloud cover to decrease due the stronger removal of cloud condensate by precipitation ~~.~~ in ice clouds. A possible explanation why changing the strength of the WBF process does not result in a significant change in cloud cover is the way saturation water vapor pressure is calculated in the cloud cover scheme. For temperatures below $0°$ C, the saturation water vapor pressure in ECHAM6 can either be calculated with respect to water or ice. As saturation water vapor pressure over ice decreases faster with decreasing temperature compared to the saturation water vapor pressure over water, relative humidity with respect to ice will be larger compared to relative humidity with respect to water at the same water vapor pressure at sub-zero temperatures. For the decision with respect to which phase state the saturation water vapor is calculated, ECHAM6 uses the same conditions as for the WBF process, so if depositional (condensational) growth of ice crystals (cloud droplets) takes place, saturation water vapor pressure is calculated with respect to ice (water). As cloud cover is diagnosed as a function of grid-mean relative humidity (Sundqvist et al., 1989), the choice with respect to which phase state the saturation water vapor pressure is calculated has a significant effect on fractional cloud cover. For the same water vapor pressure, relative humidity and therefore cloud cover will be much higher if cloud ice content exceeds γ_{thr}. This explains why enhancing the efficiency of the WBF process by choosing lower values for γ_{thr} has only a minor effect on cloud cover. As one decreases γ_{thr}, saturation water vapor pressure is more frequently calculated with respect to ice, which allows clouds to form at lower water vapor contents. Furthermore, as an existing liquid cloud starts glaciating, in this parameterization the cloud cover will increase instantaneously once the ice content exceeds the threshold. As the Sundqvist cloud cover scheme is not able to handle supersaturation with respect to ice, a grid box is also often completely cloud covered at sufficiently low temperatures (Lohmann et al., 2008; Bock and Burkhardt, 2016).

To avoid this sudden increase in cloud cover as soon as the ice water content becomes greater than γ_{thr}, we modified the calculation of the saturation water vapor pressures in the cloud cover scheme by using a weighted average between the saturation water vapor pressures over liquid water, e_l, and ice, e_i:

$$e = e_l(1 - f_i) + e_i f_i. \tag{2}$$

f_i is a weighting factor where $f_i = 0$ for a water cloud, $f_i = 1$ for an ice cloud and $0 < f_i < 1$ for a mixed-phase cloud (Korolev and Isaac, 2006). One commonly used approach to determine f_i is to define it as a temperature-dependent function that aims to resemble the partitioning between cloud water and cloud ice with decreasing temperatures (Fowler et al., 1996; Morrison and Gettelman, 20 We use a linear function that interpolates between the melting point $T_{\text{ice1}} = 0°\,\text{C}$ and the homogeneous freezing threshold $T_{\text{ice2}} = -35°\,\text{C}$ and define f_i as follows:

$$f_i = 1 - \frac{T - T_{\text{ice2}}}{T_{\text{ice1}} - T_{\text{ice2}}}. \tag{3}$$

f_i is set to 1 for temperatures lower than $-35°\,\text{C}$, while for $T > 0°\,\text{C}$, f_i is fixed to 0. In case the cloud ice content is less than γ_{thr}, we also set f_i to 0. This condition is used to delay cloud formation as long as there is not enough cloud ice for the WBF process to efficiently produce cloud ice and the phase of the clouds is predominantly liquid. Compared to the previous way of defining the saturation water vapor, this new approach introduces supersaturation with respect to ice of up to 10% for clouds in the temperature regime of mixed-phase clouds.

In Figure 7, we compare the effects of this new saturation water vapor pressure calculation (NEW) to the standard calculation for low-level cloud cover (BASE) in DJF for different settings of γ_{thr}. ~~For the standard setting of γ_{thr} the NEW implementation has its largest impact in the storm tracks of the Atlantic and the Pacific ocean, where cloud cover is reduced quite significantly, while for continental regions, almost no difference to the BASE run is simulated. In contrast to~~ As it also was found in Figure 5, Arctic low-level cloud fraction bias remains more or less unchanged in the BASE runs for a more efficient WBF process. The reduction of the ~~BASE runs, decreasing~~ liquid-cloud bias due to a more effective WBF is almost completely compensated by an increased positive bias in low-level ice clouds. This increase in low-level ice clouds can be attributed to the fact that the ice water content becomes greater than γ_{thr} and the saturation water vapor pressure is more frequently calculated with respect to ice. This enables clouds to be present even at lower value of absolute humidity compared to higher values of γ_{thr} ~~in the NEW runs reduces the cloud cover in almost all continental regions north of 60N. Some regions within Siberia and the ice covered Arctic ocean show only a small reduction in cloud cover and are comparable to~~ . Compared to standard way of calculating saturation water vapor pressure, the temperature weighted scheme is able to keep the amount of ice clouds constant while decreasing the ~~BASE runs. As temperatures in those regions easily can reach values below the homogeneous freezing threshold, only minor changes can be expected, as for both implementations saturation water vapor pressure with respect to ice is used to calculate relative humidity. The decrease in γ_{thr} also further strengthens the reduction of cloud cover in~~ amount of liquid clouds. As the amount of low-level ice clouds remains more or less constant with this newly introduced scheme, the loss in cloud cover correlates with the loss in liquid clouds due to the more effective WBF process. As stated above, tuning the WBF process alone was not able to completely remedy the overestimated amount of low-level, liquid clouds over snow and ice covered regions and additionally introduced a negative bias over oceanic regions. This explains why even with this newly introduced way of calculating saturation water vapor pressure in the cloud cover scheme, it is difficult to globally improve the amount of low-level clouds.

As we have shown in the ~~storm-track regions. Possibly, further parameter tuning of cloud microphysical processes (e. g. , reduced condensate removal by precipitation) can improve this newly introduced cloud cover bias in the oceanic regions, but this is not the subject of this study~~section above, it is difficult to tune cloud cover and phase using cloud microphysical parameterizations. As the cloud bias in ECHAM6 seems to be related to snow and ice covered surfaces, it is possible that fluxes of moisture from the surface into the atmosphere are not represented correctly in the model. In ECHAM6, turbulent surface fluxes of either heat ($\psi = h$) or momentum ($\psi = m$) are described using the following bulk-exchange formula:

$$\overline{w'\psi'} = -C_\psi \, |\boldsymbol{V}| \, (\psi_{\text{nlev}} - \psi_{\text{sfc}}), \tag{4}$$

where C_ψ is the bulk exchange coefficient with respect to ψ, $|\boldsymbol{V}|$ is the difference of the absolute wind velocity at the surface and the wind velocity in the lowest model level and the last term in parentheses is the difference of the respective quantity between the first model level (ψ_{nlev}) and at the surface (ψ_{sfc}). C_ψ can be further separated into the product of a neutral limit transfer coefficient $C_{\text{N},\psi}$ (which only depends on surface properties like surface roughness and the height of the first model level) and a (surface-layer) stability function f_ψ:

$$C_\psi = C_{\text{N},\psi} \, f_\psi \tag{5}$$

Those stability functions can be derived from Monin-Obukhov similarity theory by integrating the flux-profile relationships from the surface up to the lowest model layer but this is not practical for climate models. Therefore, ECHAM6 uses empirical expressions for those stability functions similar to the ones proposed by Louis (1979), depending on both surface properties and stability of the layer between the surface and the lowest model level (expressed by the moist Richardson number). To obtain a first impression on how cloud cover reacts to increased/decreased surface fluxes, we introduced a scaling factor μ into Equation 5 so that it becomes:

$$C_\psi = \mu \, C_{\text{N},\psi} \, f_\psi. \tag{6}$$

This scaling factor can be used to increase or decrease the neutral limit transfer coefficient which can be interpreted as a modification of the surface roughness, where values of μ greater than 1 denote higher surface roughness and stronger mixing, while values of μ less than 1 denote lower surface roughness and reduced mixing, respectively. We only modify this scaling factor for snow and sea ice covered surfaces and set it to 1 elsewhere. As before, a surface is considered snow-covered if snow height is higher than an arbitrarily chosen value of 2 cm and, a surface is considered sea ice covered if more than 50 % of a grid box is covered by sea ice. In Figure 8 we show the effect of increasing ($\mu = 5$) and decreasing ($\mu = 0.2$) mixing on low-level cloud cover over those surfaces in the northern hemisphere (for comparison we also added GOCCP cloud cover). For sea ice covered surfaces, increased mixing ($\mu = 5$) leads to reduced low-level cloud cover during winter and spring, while in summer, it leads to an increase in cloud cover compared to base run ($\mu = 1$). For decreased mixing ($\mu = 0.2$), exactly the opposite is simulated, with more clouds in winter and fewer clouds during summer compared to the basic setup. Total cloud cover behaves similarly for increased/decreased mixing whenever a grid box is snow covered (no information is available during summer as no grid box is snow-covered). If one further discriminates between liquid and ice clouds, the effect of decreasing/increasing surface fluxes mainly shows for low-level liquid clouds while the amount of low-level ice clouds remains more or less constant. By increasing surface fluxes by a factor of 5, the positive bias of liquid clouds in winter vanishes and almost perfectly matches the lidar-derived cloud mount except for fall this measure leads to an underestimated cloud amount. In general, increased mixing is expected to increase the moisture fluxes from the surface into the atmosphere and therefore to increase the moisture availability in the lowest levels of the atmosphere. While this assumption is valid for most parts of the globe, heat fluxes in the Arctic can reverse during winter so that fluxes of sensible and latent heat from the lowest layers of the atmosphere are directed towards the surface. This is due to the often observed low-level temperature inversions that also lead to qualitatively similar moisture profiles as saturation water vapor content is a function of temperature. In case of such a moisture inversion, increased mixing increases the latent heat fluxes from the atmosphere onto the surface, and this process is a sink for atmospheric moisture. In case of a temperature inversion, stronger mixing causes surface temperatures to increase, but the effect of this temperature increase on cloud cover is twofold. On the one hand, warmer surface temperatures make the atmospheric stratification less stable, which further increases mixing and consequently leads to stronger removal of atmospheric moisture by latent heat fluxes as long as the moisture inversion is still present. On the other hand, a warmer surface increases the moisture content. Consequently, the vertical moisture gradient is weakened, also resulting in weaker moisture fluxes from the atmosphere onto the surface according to Equation 4. Altogether, the increased moisture removal seems to dominate over the decrease in vertical moisture gradient, as cloud cover is reduced due to stronger mixing. Despite the potential to improve cloud cover by stronger surface mixing over snow and ice covered surfaces, it is questionable whether one can physically justify to further increase mixing as most climate models already mix too strongly in stable boundary layers (Holtslag et al., 2013). We will further elaborate on that in the next section.

5 Discussion

In the previous sections, we showed that ECHAM6 overestimates low-level cloud cover over snow- and ice-covered surfaces during wintertime compared to the GOCCP dataset. To this end, we conducted sensitivity studies to explore the effect on clouds in ECHAM6 by varying the efficiency of several physical processes. While the partitioning of liquid and ice clouds can be improved by a more effective WBF process, the overall positive cloud cover bias could not be reduced by that measure alone. We showed that this positive cloud cover bias can be improved by ~~either a more effective mixing at the surface or by~~ an alternative approach of calculating the saturation water vapor pressure in the cloud cover scheme. ~~As we have already stated in the previous section, further increasing mixing over snow and ice covered regions is not desirable as climate models in general mix too strongly under these conditions. That this is also the case for~~ Nevertheless, it is questionable to what extend a more effective WBF process in ECHAM6 can be ~~confirmed by two different aspects within the parametrization of the surface mixing in ECHAM6. In the following, we only discuss mixing over sea ice, but the conclusions are to some extent also valid for snow covered surfaces. From , we see that the bulk exchange coefficient that governs the strength of mixing in ECHAM6 is calculated as the product of the neutral limit transfer coefficient $C_{\mathrm{N},\psi}$ and a (surface-layer) stability function f_{ψ}. The roughness length for both momentum and scalars is set to $z_{0,h/m} = 10^{-3}$ m over sea ice, which is rather large compared to observations. Citing several observational studies, Gryanik and Lüpkes (2018) stated that roughness length for momentum over ice covered surface can have values ranging between $z_{0,m} = 7 \cdot 10^{-6}$ m and $z_{0,m} = 5 \cdot 10^{-2}$ m with an average value of $z_{0,m} = 3.3 \cdot 10^{-4}$ m (Castellani et al., 2014), but surface roughtness can locally be enhanced way beyond the values given by Gryanik and Lüpkes (2018), e.g. in the marginal sea ice zones or at large sea ice ridges in the central Arctic or near Greenland (Lüpkes et al., 2012). The average value is already an order of magnitude lower then the roughness length used in ECHAM6, so neutral limit transfer coefficients are also larger than the observations suggest. The same is true for the stability function f_{ψ} over sea ice in stable regimes. Gryanik and Lüpkes (2018) compared the stability functions used~~ used to improve Arctic cloud properties. Besides the effect of cloud microphysics on cloud cover, we additionally explored the effect of stronger/weaker surface mixing on cloud cover and showed that increased mixing in ECHAM6 ~~(Louis, 1979) to an alternative formulation of those functions that were derived from the SHEBA dataset (Grachev et al., 2007) and should be better suited for stable stratification over sea ice. While for weaker stability, the presently used stability functions are in agreement with this new formulation, they are considerably larger for stronger stability. As both the presently used roughness length over ice covered surface and the stability functions applied in~~ leads to a reduction of low-level clouds and by reducing liquid clouds. We will now discuss whether the two approaches can be used to tune Arctic cloud cover and cloud phase in ECHAM6~~already produce stronger mixing than observed, we think that increasing mixing efficiency even further might not be a reasonable measure to reduce cloud cover~~.

As climate models in general struggle to represent microphysical processes correctly, attributing the positive bias in cloud cover to misrepresented microphysical processes seems not to be far-fetched. ~~By exploring~~ We explored the sensitivity of cloud cover to changes in the effectiveness of the WBF process ~~, we~~ and showed that it can be used to reduce liquid cloud cover in ECHAM6. Additionally, this measure is slightly more effective over snow- and ice-covered surfaces which helps to reduce the positive bias in liquid clouds in those regions. Unfortunately, increasing the effectiveness of the WBF process alone also introduced a negative bias over oceanic regions. This hints that just revising the effectiveness of this process alone might not be sufficient to improve cloud phase on global scale. We also showed that the way microphysical processes act is not straightforward, as one might expect a higher removal of atmospheric moisture for a higher cloud ice content that should eventually decrease cloud cover. ~~Nevertheless, increasing the effectivness of the WBF processes helped to reduce the liquid cloud amount at the expense of an increased ice cloud amount. Klaus et al. (2012) found a similar increase for wintertime cloud amount for increasing and decreasing commonly used microphysical tuning parameters for this scheme in a single column setup of the regional Arctic climate model HIRHAM5 (similar, but older version of the ECHAM6 physical parametrizations). For all their sensitivity studies, cloud condensate always increased despite larger precipitation rates, so it seems that other processes overcompensated this enhanced removal of atmospheric moisture.~~ As it seems impossible to reduce cloud cover in

ECHAM6 through microphysics alone, we switched to a different approach for calculating saturation water vapor pressure in the cloud cover scheme. By using a temperature-dependent linear function that interpolates between saturation with respect to water and saturation with respect to ice, we were able to reduce cloud cover in the temperature range of typical mixed-phase clouds. Previously, the decision with respect to which phase the saturation water vapor pressure is calculated was primarily based on a cloud ice threshold to be consistent with parametrization of the WBF within the microphysical scheme. For the WBF process, such a threshold is an appropriate choice ~~because as soon as a certain amount of cloud ice is present a cloud quickly glaciates (Kärcher and Lohmann, 2003)~~as we discussed above, but when used in the cloud cover parameterization it might introduce spurious increases in cloud cover when prexisting liquid clouds start to glaciate. By using a new temperature dependent calculation of the saturation water vapor pressure, we allowed for a slight supersaturation with respect to ice in the cloud cover scheme so that relative humidity was reduced when diagnosing cloud cover using the Sundqvist scheme. Allowing for supersaturation with respect to ice is crucial to accurately represent mixed-phase and ice clouds as supersaturation with respect to ice is frequently observed in clouds that contain ice (Heymsfield et al., 1998; Gierens et al., 2000; Spichtinger et al., 2003; Korolev and Isaac, 2006). ~~That cloud cover is still positively biased in Arctic regions with very cold temperatures~~ As discussed in Dietlicher et al. (2018b), calculating the saturation water vapor pressure as a function of temperature alone might not be an appropriate choice as it does not arise from a valid solution of the Clausius-Clapeyron equation. Besides the positive effect of properly accounting for supersaturation with respect to ice in the mixed-phase temperature regime, it might also be beneficial for the simulation of cloud cover below the homogeneous freezing threshold. Even with the revised calculation of saturation water vapor pressure, ice clouds are still slightly overestimated in the Arctic (see Figure 7). This, together with the fact that ECHAM6 largely overestimates cirrus cloud emphasizes the need for a cloud cover parametrization that is designed to handle supersaturation with respect to ice even at temperatures below the homogeneous freezing threshold. First attempts to implement such a parametrization were made by Bock and Burkhardt (2016) ~~, who used ECHAM5-HAM~~ and Dietlicher et al. (2018b) for ECHAM-HAM, that uses a more sophisticated two-moment microphysics scheme that explicitly allows ice supersaturation (Lohmann et al., 2008). ~~Bock and Burkhardt (2016) primarily evaluated their new scheme for~~ Even though their revised cloud cover schemes were primarily intended to improve cirrus clouds, ~~but~~ it is to be expected that such an approach might also improve low-level cloud cover in the Arctic as those clouds often contain ice even though those schemes can not be implemented into ECHAM6 due to the simpler single-moment microphysics. Klaus et al. (2016) used a different approach to reduce Arctic cloud cover for their regional Arctic climate model HIRHAM5 (same physical parametrizations as ECHAM6 but different dynamical core). Instead of using the diagnostic Sundqvist scheme with its uniform probability density function, they used the statistical Tompkins (2002) cloud cover scheme and modified the shape of the beta function that is used as the probability density function to diagnose cloud cover. By making the beta function negatively skewed, they were able to reduce the positive cloud cover bias in their model ~~.~~ but the Tompkins (2002) cloud cover scheme is presently not available in ECHAM6 which prevents us from evaluating their approach on a more global scale.

Besides attributing the positive bias in cloud cover to misrepresented microphysical processes, we additionally focused on the effect of surface fluxes on Arctic clouds in ECHAM6. By increasing the surface mixing, we were able to improve both the biases in cloud cover and cloud phase. As we have already stated in the previous section, further increasing mixing over snow and ice covered regions might not be desirable as climate models in general mix too strongly under these conditions (Davy and Esau, 2014). That this is also the case for ECHAM6 can be confirmed by two different aspects within the parametrization of the surface mixing in ECHAM6. In the following, we only discuss mixing over sea ice, but the conclusions are to some extent also valid for snow covered surfaces. From Equation 5, we see that the bulk exchange coefficient that governs the strength of mixing in ECHAM6 is calculated as the product of the neutral limit transfer coefficient $C_{\mathrm{N},\psi}$ and a (surface-layer) stability function f_ψ. The roughness length for both momentum and scalars is set to $z_{0,h/m} = 10^{-3}\,\mathrm{m}$ over sea ice, which is rather large compared to observations. Citing several observational studies, Gryanik and Lüpkes (2018) stated that roughness length for momentum over ice covered surface can have values ranging between $z_{0,m} = 7 \cdot 10^{-6}\,\mathrm{m}$ and $z_{0,m} = 5 \cdot 10^{-2}\,\mathrm{m}$ with an average value of $z_{0,m} = 3.3 \cdot 10^{-4}\,\mathrm{m}$ (Castellani et al., 2014), but surface roughness can locally be enhanced way beyond the values given by Gryanik and Lüpkes (2018), e.g. in the marginal sea ice zones or at large sea ice ridges in the central Arctic or near Greenland (Lüpkes et al., 2012). The average value is already an order of magnitude lower then the roughness length used in ECHAM6, so neutral limit transfer coefficients are also larger than the observations suggest. The same is true for the stability function f_ψ over sea ice in stable regimes. Gryanik and Lüpkes (2018) compared the stability functions used in ECHAM6 (Louis, 1979) to an alternative formulation of those functions that were derived from the SHEBA dataset (Grachev et al., 2007) that should be better suited for stable stratification over sea ice. While for weaker stability, the presently used stability functions are in agreement with this new formulation, they are considerably larger for stronger stability. As both the presently used roughness length over ice covered surface and the stability functions applied in ECHAM6 already produce stronger mixing than observed, it is questionable if one can physically justify to even further increase surface mixing over snow- and ice-covered surfaces.

6 Conclusions

~~Correctly simulating the Arctic climate is a big challenge for climate models~~In this study, we explored potential causes for the overestimated cloud cover in ECHAM6 and identified two possibly misrepresented physical processes - cloud microphysics and surface fluxes - that might be responsible for this. Especially mixed-phased clouds pose a challenge for ~~these~~ climate models, as many of the processes acting in mixed-phase clouds are only poorly understood, which makes it even harder to develop ~~parametrizations that can represent those processes at grid sizes of a typical climate model~~cloud microphysical parametrization. As we have shown, ECHAM6 also struggles to correctly simulates mixed-phase clouds which might be attributed to the oversimplified representation of the WBF processes. Additionally, it would be beneficial to revise the cloud cover scheme to avoid the spurious increases in ice clouds as it presently is not able to handle supersaturation with respect to ice. We also explored the sensitivity of cloud cover to modified surface fluxes and showed that is possible to reduce the cloud cover bias in ECHAM6 through stronger surface mixing. As state above, increasing surface mixing even further might not be desirable in ECHAM6 but the opposite approach can be used to improve the representation of clouds in other climate models, as many of them underestimate Arctic cloud cover.

Correctly simulating Arctic climate is a big challenge for climate models. A typical feature that many models struggle to correctly simulate are the often observed two distinct atmospheric states in the Arctic: a radiatively clear state with small cloud cover or thin, ice containing clouds in combination with a strong surface-based inversion, and a cloudy state with low-level, liquid or mixed-phase clouds and only weak longwave cooling at the surface, which results in a weak and often elevated inversion (Stramler et al., 2011). Pithan et al. (2014) showed that a majority of current climate models lack a realistic representation of the cloudy state, which they attribute to an inadequate mixed-phase cloud microphysics. Our study shows that ECHAM6 is one of the few models that actually overestimates cloud cover in the Arctic. This overestimation also becomes obvious in the intercomparison of the cloud radiative effect (CRE) of several models that participated in CMIP5. Boeke and Taylor (2016) showed that the MPI-ESM-LR/MR earth system model which has ECHAM6 as its atmospheric component, exceeds the multi-model ensemble mean net Arctic CRE ($16.86\,\mathrm{W\,m^{-2}}$) by roughly $10\,\mathrm{W\,m^{-2}}$ (MPI-ESM-LR: $26.00\,\mathrm{W\,m^{-2}}$ /MPI-ESM-MR: $24.49\,\mathrm{W\,m^{-2}}$) but is in far better agreement with the CERES-EBAF net CRE of $24.22\,\mathrm{W\,m^{-2}}$. Even if the net CRE is in agreement with CERES-EBAF, the shortwave CRE (more negative) and the longwave CRE (more positive) do not match the observed values ~~, which~~ and we think that the underestimates shortwave CRE can be linked to the overestimated ~~cloud cover in MPI-ESM-LR/MR. Allowing for gentle supersaturation with respect to ice in the cloud cover scheme, we were able to reduce to observed bias in ECHAM6 to a large extent. This emphasizes the need for a cloud cover parametrization that is explicitly designed to handle supersaturation. We also explored the sensitivity of cloud cover to modified surface fluxes, and even if we were not able reduce the cloud cover bias in ECHAM6 using reasonable parameter settings, decreasing the surface fluxes in other models might help to improve the representation of the cloudy state in other climate models~~amount of liquid clouds that we have reported in this study.

Author contributions. JK and JQ this conceived this study. JM and MS helped to set up COSP in ECHAM6 and helped in conducting the model runs. MS further contributed by providing valuable expertise on the physical parametrizations of ECHAM6. All of the authors assisted with the interpretation of the results. JK prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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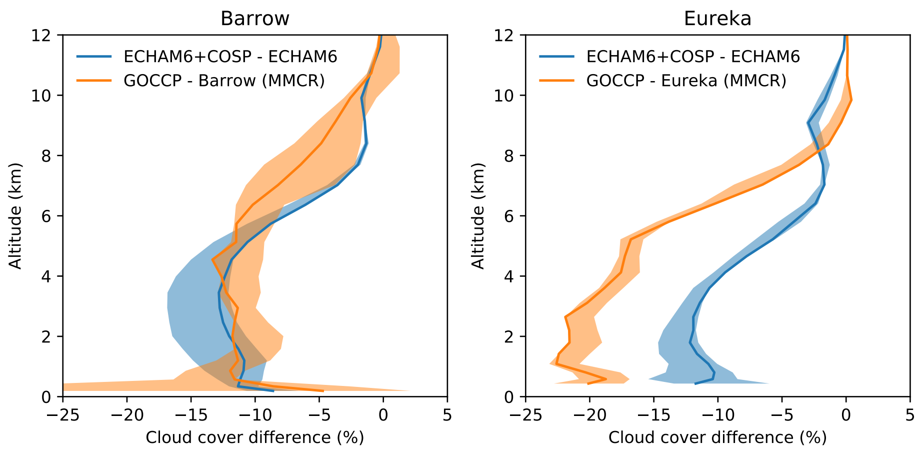

Figure 1. Difference in cloud cover profiles (from 2007 to 2009) of ECHAM6+COSP minus ECHAM6 and GOCCP minus ground based observations. Cloud cover profiles from ground based observations are derived from 35-GHz millimeter cloud radars (MMCR) in Barrow and Eureka as described in Shupe et al. (2011). Shaded areas show the effect of using the neighboring gridpoints around the location in in the grided data.

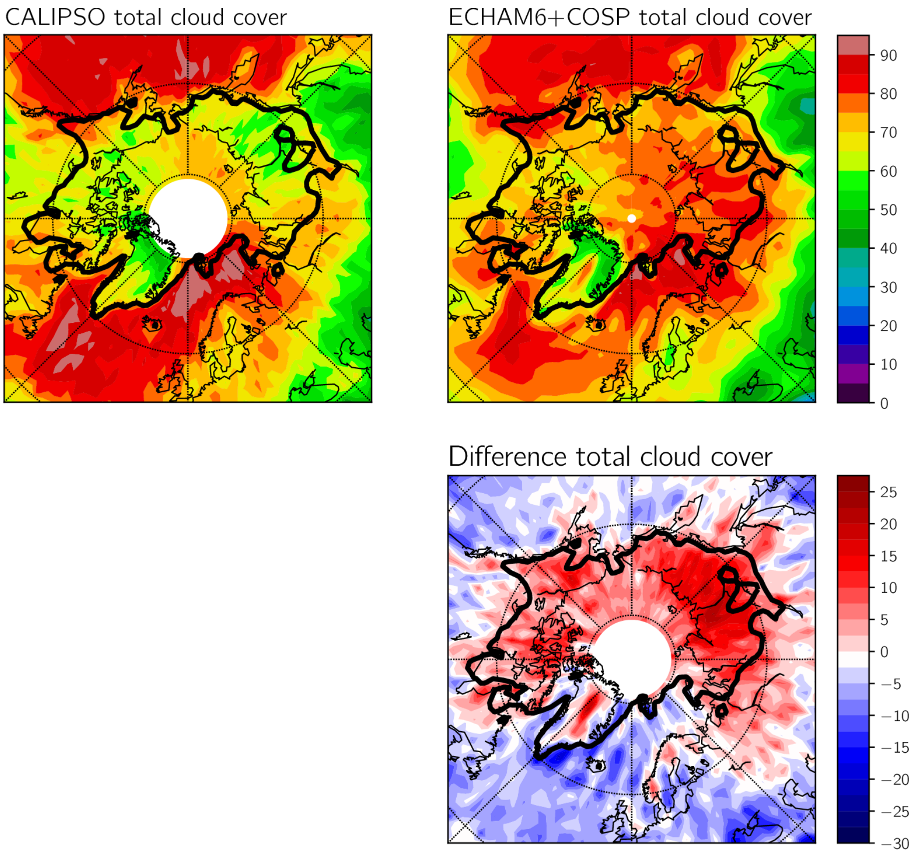

Figure 2. Top: Multi-year (2007-2011) mean total cloud cover as observed by CALIPSO and ECHAM6 + COSP. Bottom: Difference between the model and CALIPSO total cloud cover. Black line indicates regions with sea-ice cover greater then 50% or snow cover greater than 2 cm.

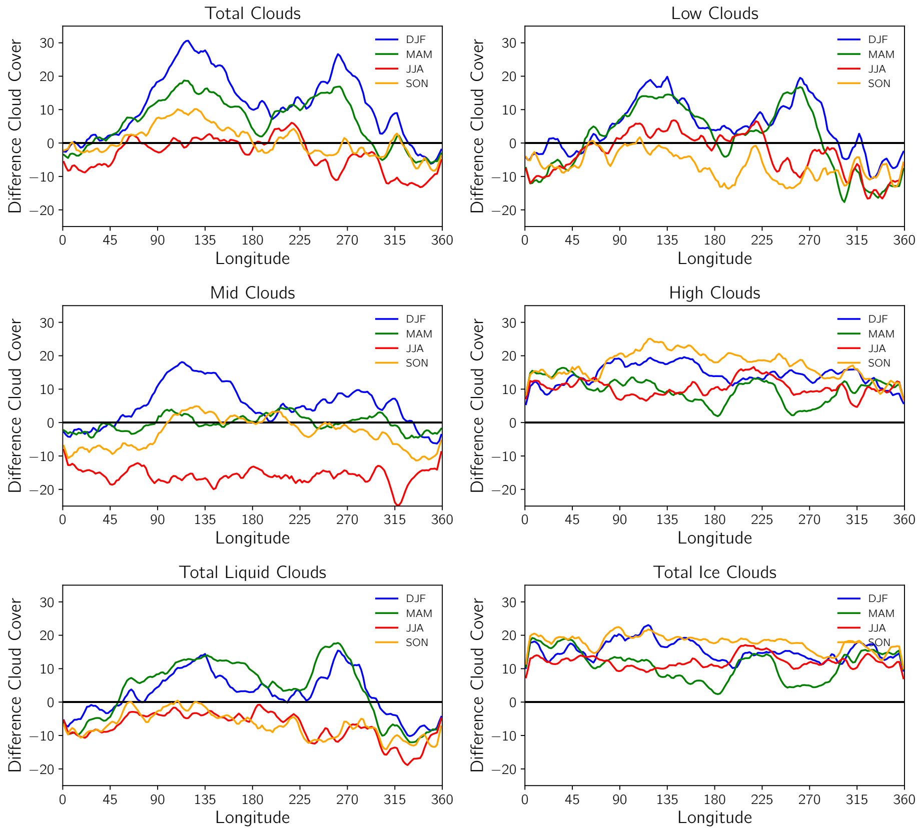

Figure 3. Meridional mean (60°N to 82°N) difference in cloud cover (model - satellite) vebetween ECHAM6 + COSP and CALIPSO for total, low, mid and high clouds as well as difference in total liquid and total ice cloud cover.

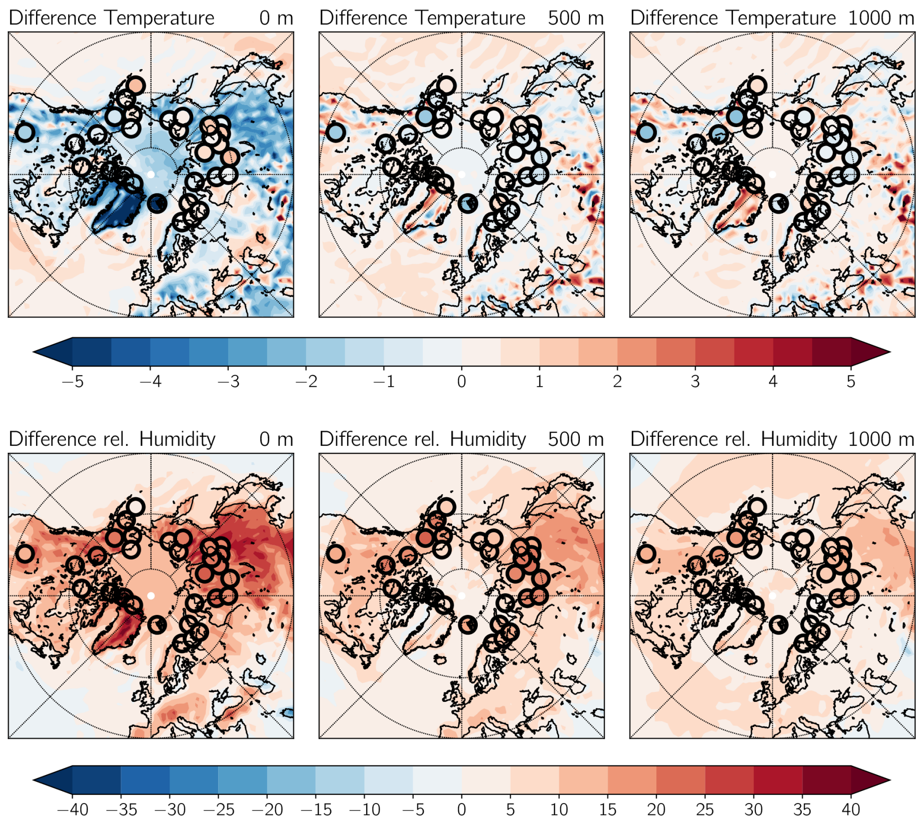

Figure 4. Vertical profiles of temperature ~~, absolute humidity~~ and relative humidity differences between ECHAM6 and ~~several radiosonde launch location north of 60N (as indicated by the red dots)~~ ERA-Interim averaged from 2007 to 2010. Filled circles show the same difference for profiles derives from radiosonde data. The vertical coordinate is height above ground level (AGL).~~Light blue shadings indicate one standard deviation.~~

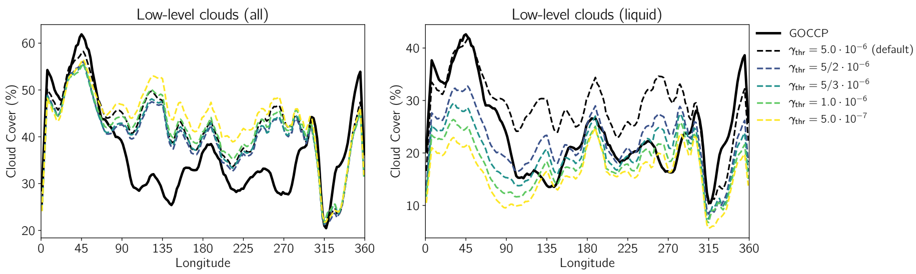

Figure 5. ~~Low-level cloud cover over sea ice~~ Meridional mean (~~left~~60°N to 82°N) ~~and snow~~ low-level (~~right~~left) ~~covered surface~~ and low-level liquid cloud cover for different ~~strenght~~ settings of ~~near-surface mixing. For CALISPO cloud cover, ice/snow cover~~ γ_{thr} (unit of γ_{thr} is ~~used from base setup.~~kg m^{-3})

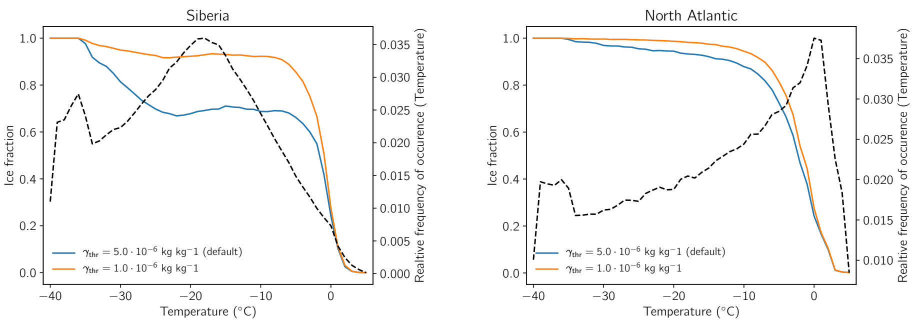

Figure 6. ~~DJF low level liquid cloud cover compared to low level total cloud cover for different values of γ_{thr}~~ Temperature-binned, averaged ice fraction (~~area-averged between 60~~IWC/(LWC+IWC)) in the North Atlantic (320-10°E / 50-70°N~~to 82~~) and in Siberia (50-130°E / 50-70°N) . The ~~black cross are~~ dashed line shows the ~~values observed from CALIPSO~~relative frequency of occurrence for the respective temperature bin.

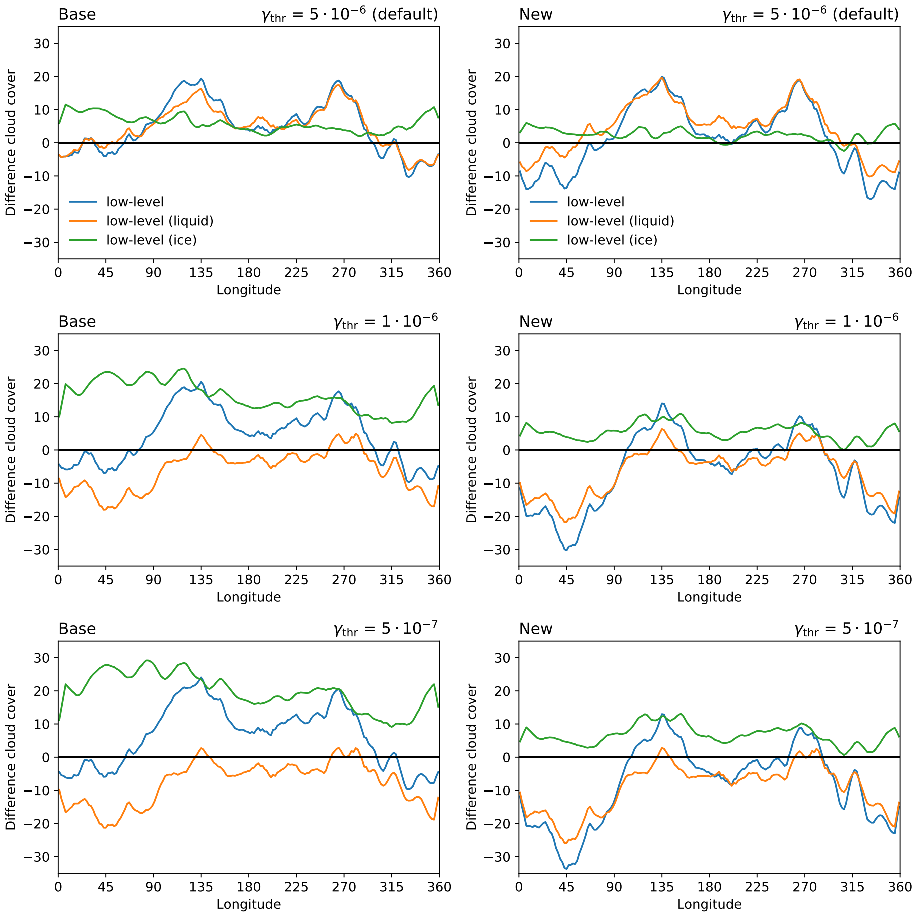

Figure 7. DJF low level cloud cover difference ~~to CALIPSO~~ (all, liquid and ice clouds) for ~~the BASE~~ standard (~~top row~~Base) and ~~NEW~~ modified (~~bottom row~~New) ~~relative humidity~~ calculation of saturation water vapor pressure in the cloud cover scheme for different values of γ_{thr}.

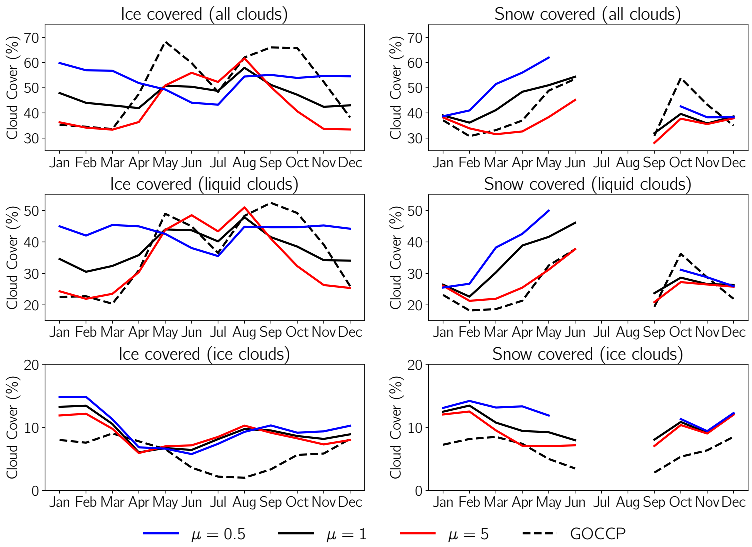

Figure 8. Nordhemispheric low-level cloud cover from ECHAM6+COSP over sea ice (left) and snow (right) covered surface for different strength of near-surface mixing for all clouds (top), liquid clouds (middle) and ice clouds (bottom). The respective GOCCP cloud cover is shown for comparison.