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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Cloud phase identification of low-level Arctic clouds from airborne spectral radiation measurements: test of three approaches" *by* A. Ehrlich et al.

A. Ehrlich et al.

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The comments of the reviewer have been helpful to improve the manuscript. Several points of the manuscript were annotated where important information was lacking. Including this information in the revised manuscript made the manuscript much more understandable. The detailed replies on the reviewers comments are given below.

The reviewers comments are given italicized while our replies are written in roman letters. Citations from the revised manuscript are given as indented text.

1 Comment 1

1) It is not clear how the determination that clouds were ice, liquid or mixed phase was made for the discussion of Figures 2 and 3.

The determination of the cloud phase was made from both in situ and cloud reflectance measurements. In the revised manuscript we describe in more detail how this was realized. See detailed replies below.

In particular, in Section 3.1, give the ranges of particles that the FSSP and CPI can measure, to help determine how this discrimination is made.

For the in situ measurements we didn't explain deeply how the phase discrimination of the cloud particles was performed. In the revised manuscript we add the following part:

> Based on in situ data, the particle phase was determined from the combination of asymmetry parameter and particle concentration measurements. The asymmetry parameter is significantly lower for nonspherical ice crystals than for spherical liquid water particles (e.g., Gerber et al. 2000). As an approximation the FSSP size range (3-27 μm) is defined to measure liquid water particles whereas the CPI (23-2300 μm) is used to determine the size distribution of large ice crystals. An analysis of the combined particle concentration and asymmetry parameter measurements (not shown here) confirms, that this assumption works sufficiently well for the mixed-phase clouds encountered during ASTAR 2007.

Is the 'ice layer' determined only from the fact that the CPI measured particles here and the asymmetry parameter is lower? Is there any evidence that this layer consists only of ice particles and has no liquid water?

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It was wrong to describe this layer as a pure ice layer. FSSP concentration and asymmetry parameter show that there are patches of water as well, probably due to cloud inhomogeneities. Also it is only a crude assumption that the FSSP measures only water particles and the CPI only ice crystals. Nevertheless, this cloud layer is obviously dominated by ice crystals. Therefore, we changed this part to:

> A thin layer dominated by ice crystals was found between 800 m and 1100 m, indicated by lower asymmetry parameters.

By what instrument were the precipitating ice particles down to 500m observed? Also, it would be nice to put the profile of in situ measurements in Figure 2 into context.

So we did:

> Below this layer, precipitating large ice particles were observed down to 500 m by visual observation on board the aircraft and from in situ measurements indicating a low particle concentration (CPI and FSSP) and a low asymmetry parameter measured by the Polar Nephelometer.

Was it the only in situ profile taken on these days during the experiment or the only one in a mixed phase portion of the cloud? What part of the flight track in Figure 1 does it correspond to?

No, a total of 16 vertical profiles were obtained with 14 showing a structure similar to the mixed-phase cloud presented here. We have add the following text and indicated the exact measurement sites in Figure 1 (see revised manuscript).

> In situ measurements have been obtained from a total of 16 vertical profiles flown between April 7-9. Except for two profiles taken at the edge of the cloud fields where pure ice clouds were observed, the in situ measurements generally show the typical structure of the prevailing mixed-phase clouds with a cloud top

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> layer consisting of liquid water and precipitating ice crystals below. ... A typical profile of measured particle concentration and asymmetry parameter obtained on April 7 between $78.0°$ N and $78.5°$ N (cp. Figure 1 label A) is presented in Figure 2.

In Section 3.3, how were the periods of mixed phase, pure ice, and pure liquid plotted in Figure 3 identified?

The clouds have been identified independently by analysis of the measured spectral reflectance and the in situ measurements. Only for the water cloud no in situ measurements were available. Nevertheless, already the analysis of the spectral reflectance revealed significant differences which are caused by the water and ice absorption as discussed in Section 3.3. Even without calculating an ice index, a qualitative statement on the cloud thermodynamic phase could be made. In the revised manuscript we have added the following sentences to show that the cloud phase was not only assumed from the reflectance measurements. Additionally, we point out more clearly that the presented microphysical measurements are partly related to this clouds.

> The thermodynamic phase of the ice and mixed-phase clouds presented here has been verified independently by the in situ measurements as described in Section 3.2. The ice cloud is investigated in a case study described in Section 6.

And how were the optical depths for each cloud calculated?

We use standard retrieval techniques utilizing the cloud reflectance at one visible (645 nm) and one absorbing wavelength (1650 nm) for which precalculated tables for different clouds have been simulated and afterwards compared to the measurements. This method is described in detail by Nakajima and King (1990). The following part has been added to the revised manuscript:

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> Especially the liquid water cloud shows differences of R_λ in the wavelength range between 500 nm and 1300 nm as shown in Figure 3a. These differences result from different cloud optical thickness τ. We retrieved τ for the clouds presented here by applying standard retrieval techniques (Nakajima and King, 1990). The mixed-phase cloud assumed as liquid water cloud for the retrieval has a τ of 12, while for the ice and pure liquid water cloud $\tau = 4$ and $\tau = 15$ was found, respectively.

What are the error bars on the plots?

In Figure 3 the error bars indicate the measurement uncertainty of the reflectance measurements, not the variability along the time period as one may assume. In the figure caption we added:

> Error bars indicate the measurement uncertainty of the reflectance measurements.

Were multiple reflectance measurements averaged over some flight track/time period for the plot?

Yes, the measurements are averaged. This is now pointed out more clearly by:

> All measurements shown here are averaged over the time period the cloud was sampled (mixed-phase cloud 18 min, water cloud 8 min and ice cloud 2 min).

Do the areas of ice, liquid, mixed phase correspond to particular elements of the flight track or MODIS image in Figure 1?

Yes, they do. We added labels in Figure 1 of the revised manuscript. Additional have add the following in Section 3.3 and in Section 6:

> The mixed-phase and ice clouds were observed during the first flight on April

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7 as indicated by the labels A and C in Figure 1. Measured microphysical properties of the mixed-phase cloud are discussed in Section 3.2. The water cloud was sampled during a second flight on April 7 between 75.4° N, 11.5° E and 75.8° N, 11.8° E.

On April 7, 2007, concurrent radiation and microphysical measurements were conducted along the path of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO) over the Greenland Sea as marked in Figure 1 with B.

2 Comment 2

2) The definition of 'mixed phase' cloud throughout the paper is unclear. Please define what you mean by mixed phase cloud - is it defined as cloud with ice and water in the same layer, or ice and water in the same column? In the sensitivity studies presented in Figure 4, how is the 'Mixed' cloud calculated? Is it a liquid layer above an ice layer or liquid/ice particles in the same layer? What is the ratio of ice and water mass in the mixed layer?

Generally, the definition of a mixed-phase cloud is that ice and liquid water particles coexist in a certain cloud volume. Otherwise, there are different options to realize this mixture, either as homogeneous mixing or as different layers. The simulation we present in Figure 4 is performed for a single-layer homogeneous mixed cloud. It is part of systematic simulations for mixed-phase clouds not presented here, where ice volume fraction was varied. For this extensive calculations we have chosen the homogenous mixing. We know that this is only a crude approximation as the in situ measurements show a distinct vertical distribution of ice and liquid water. Therefore, investigations on the impact of the vertical distribution of ice and liquid water particles on radiative transfer are presented in Section 5.2. Here we consider the distinct ice and liquid water layers and estimate how the vertical distribution affects the ice indices. Additionally, we

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are about to investigate this issue in more detail. The results will be part of another manuscript, what is in preparation for ACPD. In the revised manuscript we have add the following sentences.

> Results of the radiative transfer simulations for clouds comparable to the observed ice, liquid water and mixed-phase clouds ($\tau = 12$) are given in Figure 4. To illustrate the spectral differences between 1450 nm and 1750 nm the effective diameter of the ice crystals ($20\ \mu$m) and liquid water droplets ($10\ \mu$m) used in the simulations has been chosen to yield a similar magnitude of R_{1600}. The mixed-phase cloud was simulated as a single-layer homogeneous mixed cloud with an ice volume fraction of 0.5.

And changed the introduction to Section 5.2:

> Generally, the definition of a mixed-phase cloud is that ice and liquid water particles coexist in a certain cloud volume. For radiative transfer simulations there are different options to realize this mixture, either as a homogeneous mixed single-layer cloud or as a multi-layer cloud with distinct pure ice and liquid water layers. From the in situ measurements presented in Section 3.2 it follows that boundary-layer mixed-phase clouds typically consist of two layers with liquid water droplets at cloud top and precipitating ice below. In this sensitivity study we focus on the ability to identify such mixed-phase clouds and how the layering affects the cloud phase retrieval.

3 Comment 3

3) For the ice scattering calculations, columns were used. Is there any evidence that low-level Arctic ice/mixed-phase clouds contain columns? How sensitive are the ice

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indices to the habit assumption used?

The first reason why we used columns is that up to now the single scattering properties calculated for the entire wavelength range used in the manuscript and the CPI size bins are available only for columns. Calculations for different crystal shapes as aggregates or plates are still not completed. Nevertheless, as we simulate the cloud for predetermined effective diameter, the particle shape is of less importance for the wavelength range where the ice absorption is high. The magnitude of absorption is directly linked to the effective diameter. For the same reason the ice indices are also less sensitive to ice crystal habit. With regard to ice index I_A the scattering phase function between $95°$ and $110°$ is almost independent of the ice crystal shape, especially if it is taken into account that the large difference to liquid water droplets is utilized for this ice index. The following text is added in the revised manuscript:

> For the simulations presented here the choice of the particle shape is of less importance. With regard to the wavelength range where ice absorption occurs, the predetermined effective diameter of the cloud particles characterizes the absorption independent of the particle shape. For the reflectance at visible wavelengths the scattering phase function of the ice crystals is crucial. However, the part of the scattering phase function relevant for the solar zenith angles observed during ASTAR 2007 is similar for different ice crystal shapes as shown below in Section 4.3 and Figure 8.

4 Comment 4

4) Section 5.1. The authors mention that to achieve reliable information on cloud phase, a priori knowledge about ice crystal effective diameter and optical depth are needed (as shown in the sensitivity studies), but do not discuss what the typical uncertainties on such measurements are. Also, there is the problem that visible optical depth

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retrievals are very sensitive to the scattering phase function assumed in the retrieval. Given that the instruments used have visible and near-IR channels (which are sensitive to optical depth and particle size, respectively), a retrieval of optical depth and effective diameter could be performed along with the phase retrieval. This would allow a more sophisticated sensitivity study, which would include the actual errors likely in retrieval of optical depth and particle size.

The conclusion that information on ice crystal effective diameter and optical depth is needed may have been misunderstood in the way we wrote. Generally, for the calculation of the ice indices no assumption on the cloud optical thickness τ is required. Our aim was to define ice indices which can be interpreted independent of any assumption or retrieval of τ and effective diameter. Reliable retrievals of cloud properties from remote sensing handle ice and liquid water clouds separately. The first step is to identify the cloud phase. Assuming the wrong cloud phase will result in large uncertainties of the retrieved cloud properties. To obtain independent ice indices, normalization by the cloud reflectance at particular wavelength is applied for I_{S} and I_{P}. I_{A} deals with this issue differently as explained in the revised manuscript. However, the ice indices change slightly with τ, especially for $\tau \leq 10$ and for I_{S}, I_{P} more strongly with particle effective diameter. Nevertheless, the sensitivity study has shown (and that was its aim), that there is almost no ambiguity for the discrimination of pure ice and liquid water clouds for all three ice indices. That means that for the discrimination of pure ice and liquid water clouds no assumption or retrieval on τ and D_{eff} is required. Only in the case of mixed-phase clouds knowledge on τ and D_{eff} becomes necessary for I_{S} and I_{P}, because for ice clouds I_{S} and I_{P} increase with τ and D_{eff}. The ice indices obtained for a mixed-phase cloud range between a minimum value given by a liquid water cloud and a maximum given by an ice cloud with D_{eff} equal to the D_{eff} of the mixed-phase cloud. If D_{eff} and with it the maximum values are not known, the ice indices of the mixed-phase cloud may be interpreted as pure ice cloud with smaller D_{eff}. In the case study presented in Section 6 the measured effective diameter of 85 μm is used to interpret the ice indices. The measured D_{eff} is used to estimate the maximum value of I_{S} and I_{P}

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corresponding to a pure ice cloud. From the good agreement of simulated ice index of a pure ice cloud assuming $D_{\text{eff}} = 90\,\mu$m and the ice index measured above the pure ice cloud we conclude that the case study is not affected significantly by uncertainties in the measured D_{eff}. To point out this more clearly in the manuscript, we have changed following parts in Section 5:

> In the following we discuss the impact of cloud optical thickness and particle effective diameter on the unambiguousness to discriminate pure ice and pure liquid water clouds by the ice indices defined in this paper (Subsection 5.1).

In Section 5.1 we changed the conclusions to:

> The discrimination of pure ice and pure liquid water clouds is almost unambiguous. With regard to an identification of mixed-phase clouds a priori knowledge of D_{eff} and τ is needed. The ice indices obtained for a mixed-phase cloud range between a minimum value given by a liquid water cloud and a maximum given by an ice cloud with D_{eff} and τ equal to the values of the mixed-phase cloud (not shown here). If D_{eff}, τ and accordingly the maximum values of I_{S} and I_{P} are not known, the ice indices obtained for the mixed-phase cloud may indicate a pure ice cloud with smaller D_{eff} or smaller τ.

In Section 5.2 the interpretation is supplemented by:

> The maximum values of $I_{\text{S}} = 41$, $I_{\text{P}} = 3.3$ and $I_{\text{A}} = 1.08$ range above typical values for pure liquid water clouds and below the maximum values of an ice cloud with equal $D_{\text{eff}} = 85\,\mu$m and $\tau = 15$ as used in the simulations of the mixed-phase cloud (cf. Figure 5, 7 and 11).

In Section 7 the conclusions are pointed out more clearly by:

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Nevertheless, an ambiguity in the discrimination of ice and liquid water phase occurs only between pure ice clouds with small ice crystals and low τ and pure liquid water clouds of high τ. More crucial is the dependence on the ice particle effective diameter for the discrimination between mixed-phase and pure ice clouds. Here, a priori knowledge about the ice crystal dimensions is required.

One question I am left with after reading the paper is, given the large variability in Is and Ip with particle size and optical depth (for tau < 10), and the likely uncertainty in those values, what fraction of the mass (or optical depth) of a mixed phase cloud would have to be water for the cloud to be clearly distinguished from a pure ice cloud?

That depends on how large the effective diameter of the ice crystals is. The larger the ice crystals, the larger the differences in the ice indices of the two extremes, the pure ice and pure liquid water cloud. The larger this difference, the more distinct is the separation of mixed-phase clouds from pure water clouds. As shown in Section 5.2 for $D_{\mathrm{eff}} = 85\,\mu$m and $\tau = 15$ an ice fraction of $\tau_{\mathrm{Ice}} = 1.5$ is sufficient to change the ice indices.

A general conclusion on the detection limit of mixed-phase cloud is not possible due to the dependence on the effective diameter. Therefore, we state that for the identification of mixed-phase clouds a priory knowledge on D_{eff} is necessary. The verification of the detection limit for various D_{eff} and $\tau = 15$ was beyond the scope of this manuscript.

5 technical comments

1. Define SMART when first mentioned (p. 15905, line 1).

Is corrected in the revised manuscript.

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2. Section 4.2, 2nd paragraph. Are these tau and Deff the same values discussed at the beginning of section 4 and used in the sensitivity study for Is? If so, do not repeat them here.

This has been removed at in this section of the revised manuscript.

3. In discussion in Section 5.1 about optically thin clouds, I believe that Is and Ip have been mixed up as Ip shows values much closer to liquid values for thin ice clouds than Is does.

Here the ambiguity of I_S for thin ice clouds and thick liquid water clouds was meant. I_P does not show such an ambiguity. We have changed the following sentence:

> Especially for optically thin ice clouds I_S can reach values of pure liquid water clouds with high optical thickness.

4.p. 15913, What is the explanation for the fact that R for wavelengths < 1300 nm is different for mixed phase and pure ice clouds in the simulations, while in the observations they are the same?

Here we put the wrong optical thickness in the caption of Figure 9. The ice cloud has a lower optical thickness of $\tau = 12$ than the mixed-phase cloud with $\tau = 15$. Despite the different optical thickness, both clouds have the same R which can be explained by the scattering phase function as described in Section 4.3. In the simulations presented before the optical thickness of all clouds is the same. Therefore here, R differs with cloud thermodynamic phase. In the revised manuscript we have corrected the caption of Figure 9.

> Cloud top reflectance R_λ and cloud albedo α_λ measured on April 7, 2007, above a mixed-phase cloud (a) of ($\tau = 15$) and a pure ice cloud (b) of ($\tau = 12$) introduced in Section 3.3 and Figure 3.

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5. What particle size is used for the cloud simulations shown in Fig 4?

The specification of the particle size used in the simulations for Figure 4 are now included in the manuscript.

> To illustrate the spectral differences between 1450 nm and 1750 nm the effective diameter of the ice crystals ($20\,\mu$m) and liquid water droplets ($10\,\mu$m) used in the simulations has been chosen to yield a similar magnitude of R_{1600}.

6.Section 5.2; sensitivity to vertical distribution. How sensitive are the values of Is and Ip (or their relative magnitudes) to the choice of ice and liquid Deff? If a smaller ice Deff were chosen, would you still be able to identify the cloud as mixed phase?

Yes, it is correct that D_{eff} affects the values if I_S and I_P. Most important is D_{eff} of the ice crystals as we discussed in Section 5.1. Consequently the choice of D_{eff} also affects the study presented in Section 5.2. A smaller D_{eff} of the ice crystals will reduce the differences in I_S and I_P and so the sensitivity of the ice indices. Nevertheless, the study was based on the clouds observed during ASTAR 2007 where $D_{\text{eff}} = 85\,\mu$m measured for ice particles and should illustrate that in this case it is possible to identify mixed-phase clouds. In the revised manuscript we add the following text regarding this comment.

> It has to be pointed out that the sensitivity of I_S and I_P to mixed-phase clouds will be reduced if a smaller D_{eff} of the ice crystals is assumed. Smaller ice crystal have less absorption which results in reduced differences of I_S and I_P between pure ice and liquid water clouds (cp. Figure 5 and Figure 5).

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