Atmospheric Chemistry and Physics Discussions

Interactive Comment

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.

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The comments of the reviewer have been very appropriate. They helped to find weak points in the description of the methods presented in the manuscript. Including the changes in the revised manuscript improved the focus on the main conclusions of the presented study. 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.

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1   Comment 1

1. The two-wavelength approach, described in Section 4.1, relies entirely on the differences (between liquid water and ice clouds) in the slope of reflected radiance in the near-infrared band between 1550-1700 nm. The utility of this parameter comes directly from the differences in the imaginary part of the refractive index between liquid water and ice. However, by not normalizing by the radiance at a non-absorbing (shorter) wavelength, the authors have not utilized the fact that ice is far more absorbing (about a factor of 4, I think) in this same spectral region. If this can be included in the parameter IS it will become far more effective in discriminating phase. (This was essentially the main point in Pilewski and Twomey, 1987, cited in the manuscript). There will remain an ambiguity due to particle size but I will discuss that later.

In our manuscript I_S is calculated from the cloud reflectance normalized by R_{1640}. Therefore, the higher absorption of ice crystals is already taken into account since R_{1640} decreases and accordingly I_S increases for enhanced absorption. The reviewer suggests to include the magnitude of absorption by multiplying the current parameter by the ratio of reflectances R at a nonabsorbing and an absorbing wavelength R_{1640}/R_{860}. This ratio was used by Pilewskie and Twomey, 1987, for identifying the cloud phase since ice clouds have a higher R_{860} and absorb more radiation at 1640 nm, which reduces R_{1640}. By multiplying I_S by the ratio R_{1640}/R_{860} the discrimination between pure ice and liquid water clouds is improved,

$$\hat{I}_S = \frac{R_{860}}{R_{1640}} \cdot I_S. \tag{1}$$

We have followed this approach suggested by the reviewer and have calculated $\hat{I}_S$ for the simulated clouds described in the manuscript (Section 4.0). The sensitivity of $\hat{I}_S$ as a function of cloud optical depth and particle effective diameter reveals that the differences between liquid water clouds and ice clouds are enhanced. The impact of cloud optical thickness on the revised index $\hat{I}_S$ for the water cloud can almost be

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neglected. Nevertheless, for ice clouds $\hat{I}_S$ is dependent on both effective diameter and optical thickness. Compared to I_S which is less dependent on τ especially for high values of τ, this is a disadvantage, because $\hat{I}_S$ is not able to identify mixed-phase clouds. Assuming a fixed known ice crystal effective diameter, changes of $\hat{I}_S$ may result either from variations of the ice fraction or from variations of τ. I_S changes only with variation of the ice fraction if ice crystal effective diameter is fixed. Therefore, we are still convinced that I_S is more appropriate for the identification of mixed-phase clouds than the revised parameter suggested by the reviewer. However, $\hat{I}_S$ is more efficient to discriminate pure ice and pure liquid water clouds.

By the way, the PCA index, described in section 4.2 does normalize by radiance at a non-absorbing wavelength to remove the influence of cloud optical thickness. The same should be done here.

I_P is somewhat different from I_S. In I_P the ratio of the two principle components PC_I and PC_W is calculated. PC_I and PC_W decrease with increasing absorption and with increasing particle effective diameter. Thus, the magnitude of absorption is considered here as well.

2   Comment 2

First of all, presumably the analysis was conducted over a limited set of scattering angles (equivalently, solar zenith angles, since the measurements were made at nadir), based on the phase functions shown in Fig. 8? Perhaps I missed it but are the calculated scattering angles the same as the range of measurements (zenith angle between 70 to 85 degrees) or just at a single angle?

No, all measurements and simulations shown here have been conducted at solar zenith angles of about $\theta = 70°$. In Figure 8 the range for the entire ASTAR campaign is marked as a gray strip to illustrate that this method would work for the conditions encountered

during the entire campaign. We have included the exact θ of the simulations and measurements into the revised manuscript.

And on p. 15913, l. 18, how is the scattering angle between 95-110 degrees for nadir viewing with the solar zenith between 70 to 85 degrees? Shouldn't it be 70 to 85 degrees?

No, it is indeed $95°$ to $110°$ for the scattering angle. For the nadir viewing geometry the scattering angle can be calculated with the solar zenith angle θ by $\vartheta = 180° - \theta$. For θ ranging between $70°$ and $85°$ the corresponding scattering angles ϑ are between $95°$ and $110°$.

However, these are other issues with the use of this parameter that need to be resolved. The parameter derived on p. 15914, l. 16, can be simplified as the ratio between the calculated albedo of water cloud to the measured albedo, divided by the calculated reflectance of a water cloud. If all things are known a priori, this should work. But if cloud optical depth is poorly known, it appears that would dominate this parameter.

It seams that the notation of equation 4 is not clear. We apologize for that. The denominator β_I^{water} meant to be a function of R_{645}^{meas}. Therefore, it is not a product of β_I^{water} and the parenthesis. A detailed reply to the comments related to I_A is given below for Comment 3.

3 Comment 3

3. Two issues in the section on sensitivity studies should be addressed. The first has to do with the impact on cloud particle size. It was mentioned in the first comment that particle size could lead to ambiguous phase discrimination. However, this was addressed by Pilewskie and Twomey, . J. Atmos. Sci., 44, 3419 (1987), which was a follow up to their first paper to specifically address this ambiguity. Part of the solution

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was to incorporate measurements beyond 2 μm, where the absorption of ice and liquid water are closer in magnitude than in the 1.6 μm window. This, along with the spectral shape, can completely remove ambiguities due to particle size. The authors state that their measurements extend to 2.1 μm. Why weren't the measurements at those wavelengths used?

We have not seen that absorption of ice and liquid water are closer for wavelengths larger than 2 μm. The differences look even larger at most wavelengths. Only at about 1975 nm and 2150 nm absorption is equal. Additionally, there is a strong CO_2 absorption band between 1900 nm and 2100 nm what may cause complications. Furthermore, the uncertainty of the reflectance measurements increase for this wavelengths range as the sensitivity of the spectrometer decreases. Therefore, we decided not to use the measurements at wavelength larger 1900 nm for the cloud phase retrieval.

Nevertheless, using a wavelength where both ice and liquid water absorption are equal does not change the physical concept of the spectral slope ice index. Considering cloud reflectance measurements at a single wavelength where ice and water absorb equally, the reflectance give information on the magnitude of absorption only, but would not unambiguously reveal which phase the particles have. Of course, as stated by the reviewer the ice crystals are usually larger than liquid water droplets and therefore have a higher cross section. This increases the magnitude of absorption for ice crystals. This effect is incorporated in the spectral slope ice index by normalizing the spectral slope by R_{1640}. Using a different wavelength does not improve the phase identification.

What counts is a) the spectral differences (slope) for at least two wavelengths where ice and liquid water absorption is at one wavelength close to each other and more different at the second wavelength. It does not make a difference if a wavelength is used where ice and liquid water absorption is equal. Only the spectral difference is important. b) the magnitude of absorption characterized by the reflectance at one particular wavelength. Except a) and b), there is no more information to use, even if different wavelengths are applied. These are always the same mechanisms a) and b).

Whereby b) alone can only indicate the particle size commonly larger for ice crystals, but not the thermodynamic phase itself.

The second issue that I think needs to be addressed is the sensitivity to cloud optical thickness. I understand what the authors did and how they interpreted their results in figures 5, 7, and 11. However, the assumption in all of this analysis is that optical depth is known. A more appropriate test, in my opinion, would be sensitivity to the error in optical depth.

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 assumptions on τ and effective diameter. Therefore, normalization with the cloud reflectance at a particular wavelength was applied for I_S and I_P. I_A deals with this issue differently as explained by the subsequent replies below. However, the ice indices change only 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, that there is almost no ambiguity for the discrimination of pure ice and liquid water clouds for all three ice indices. That means that no assumption or retrieval on τ and D_{eff} is required for the discrimination of pure ice and liquid water clouds. 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 values 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 accordingly 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}. To point this out more clearly in the manuscript, we have changed the 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 was 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 $D_{\text{eff}} = 85\,\mu\text{m}$ 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:

> 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.

As it was pointed out in comment 2, the angular dependent index will have a huge problem if cloud optical depth is poorly known. And that leads to the following question: was optical depth for these analyses always derived from the in situ measurements? If so,

there is plenty of opportunity for large errors due to on sampling issues related to the in situ profiling versus the optical derived parameters. The same cloud-top spectral radiation measurements applied to this study can be used to retrieve cloud optical thickness and effective particle size. Have these been compared with the in situ measurements of the same? This I see as perhaps the biggest limitation in determining the sensitivity to optical thickness and perhaps the utility of IA. This may even explain to ambiguity in interpreting cloud phase from figure 13.

As described above, I_A does not require an assumption about the cloud optical thickness. It seems obvious to us that the description of I_A was not clear enough. Here we supply a detailed definition:

First considering only water clouds with liquid droplets: For $\theta = 70°$ the cloud albedo α is always higher than the nadir reflectance R due to the minimum in the scattering phase function for the scattering angles of this geometry. That means that the reflected radiation is anisotropic. Therefore, we introduce the ratio β as a kind of anisotropy index. β is always lower than 1. $\beta = 1$ would mean, that the radiation is reflected isotropically, i.e. $\alpha = \pi R$. With increasing cloud optical depth both α and R increase. But the increase of R is stronger (more multiple scattering, less information on the scattering phase function maintains, more isotropically reflected radiation). Therefore β increases as well with cloud optical depth. This dependence follows a quite regular curve as we have shown by simulations (Figure 10, blue crosses). Remarkably, all blue crosses are results for different cloud optical depths and effective particle sizes! That is that the blue line parameterizes a variety of liquid water clouds for the assumed geometry (θ, nadir view, altitude).

Now considering ice crystals: Ice crystals reveal higher sideward scattering for the scattering angles considered here. Therefore, R is larger and closer to α than for water clouds (Figure 9). Accordingly, β is higher. But also β for ice clouds increases with cloud optical depth (Figure 10). Therefore, using only β will yield an indicator for the cloud phase only, if we know the optical depth of the cloud.

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Our aim was to define an indicator which can be applied without knowledge of the cloud optical depth. And from our measurements we learned that R increases with optical depth. A conventional retrieval of optical depth was avoided in the following way. From the measurements we get a β_{meas} and a R. Our first assumption is, that the cloud is a liquid water cloud. With the measured R we obtain a theoretical value for β_{sim} from the parametrization for liquid water cloud presented in Figure 10. If measurements were obtained over an ice cloud, β_{meas} will be larger than β_{sim}. This is how the index I_{A} is defined. In general, it is nothing else than plotting the measurements into Figure 10 and comparing them to the simulated blue line for liquid water clouds (cp. Figure 13).

Parts of this detailed description have been included in the revised manuscript Section 4.3:

> Based on these findings, we suggest the ratio of cloud top reflectance and albedo at 645 nm wavelength $\beta_{\text{l}} = R_{645}/\alpha_{645}$ as an indicator of the anisotropy of the radiation field reflected at cloud top. For the geometry presented here with $\theta = 71°$, β_{l} is always lower than 1 whereby nonspherical particles give a higher β_{l} than spherical particles. $\beta_{\text{l}} = 1$ would mean that the radiation is reflected isotropically, i.e., $\alpha = \pi R$.

> With increasing cloud optical thickness both α and R increase with a stronger increase for R. Increased multiple scattering diminishes the information of the scattering phase function and leads to more isotropically reflected radiation. That is why also β_{l} increases with cloud optical thickness. This relation is plotted in Figure 10 using R_{645} as a measure of cloud optical thickness on the abscissa. The data result from simulations of pure liquid water clouds and pure ice clouds presented above. Both liquid water and ice clouds show a distinct relation between β_{l} and R_{645}, with the isotropy of the reflected radiation being significantly higher above ice clouds than above liquid water clouds of the same R_{645}. These differences can be utilized to identify the cloud phase.

Therefore, we have parameterized β_I for the simulated liquid water clouds as function of R_{645} by the polynomial fit shown as a blue solid line in Figure 10. This parametrization is valid for the assumed geometry (θ, nadir view, flight altitude) and the entire variety of liquid water clouds (τ, D_{eff}) provided by the simulation. This leads us to the definition of the anisotropy ice index I_A as the deviation of the measured β_I^{meas} from the β_I^{water} parameterized for liquid water clouds. I_A is calculated as the ratio

$$I_A = \frac{\beta_I^{\text{meas}}}{\beta_I^{\text{water}}}. \tag{2}$$

Therefore, β_I^{water} is obtained from the polynomial fit using the measured value of R_{645}^{meas}. Using R_{645}^{meas} incorporates indirectly the cloud optical thickness and reduces their impact on I_A. From the definition of I_A it follows that we obtain $I_A = 1$ for pure liquid water clouds and $I_A > 1$ for pure ice clouds.

4   Minor Comments

1. In the abstracts the three indices were listed but not described. Better to give a short description (slope, pca, and angular) rather than just listing the symbols.

The description of I_S and I_P was quite short. Therefore, we expand the description of the indices to the following sentence.

While I_S analyzes the slope of the spectral reflectance in this wavelength range, I_P utilizes a principle component analysis of the spectral reflectance at the same wavelengths.

2. P. 15908, line 12, the formula for R: this is a non-standard definition. It is missing the cosine of the solar zenith angle to make it equivalent to the standard definition of

reflectance function (in Chandrasekhar, for example).

We added the following sentence to emphasize the meaning of irradiance:

> The irradiance presented here is measured with respect to a horizontal plane $F_\lambda^\downarrow = F_\lambda^\downarrow(\cos\theta)$ with θ giving the solar zenith angle.

3. Equation 1: is it the average slope over this spectral domain computed? How: ratio of mean radiance in the entire band to total wavelength difference, or the mean of the slopes in each wavelength interval in the band (it should be the latter)?

The slope of the reflectance has to be calculated with care. The problem for our measurements is that there is noise in the measurements of the NIR spectrometer caused by the spectrometer characteristics. Additionally, absorption by CO_2 complicates the calculation of the slope. Therefore, first we exclud measurements at wavelengths with CO_2 absorption from our calculations. To overcome the noise of the measurements we perform a linear regression over the wavelength range between 1550 nm and 1700 nm. From this linear fit we finally derive the slope of the spectral reflectance used in Equation 1. This procedure is already explained within the text of the manuscript.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 15901, 2008.

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