

We thank the reviewer for the careful and thoughtful review. Our responses are outlined in bold and italics below.

This manuscript summarizes efforts to obtain an ensemble of cloud properties from surface-based observations at the ARM site near Barrow, Alaska. A majority of the effort is spent on describing the methods and information provided by the high spectral resolution infrared observations of the AERI instrument, but these observations are complemented by other active profilers in the proposed retrieval algorithm. Cloud retrievals from surface-based instruments remain a major challenge. It takes a high degree of creativity to consider the full scope of the parameter space, combine together multiple sensors to constrain as best as possible the geophysical quantities within that parameter space, address the uncertainties in a physically consistent way, and develop a retrieval approach that can be automated and executed on a large set of data beyond simple case studies. This kind of work is detailed and tedious, but important for pushing the boundaries with regard to improved knowledge of cloud properties. Surface-based observations are not only essential for detailed scientific studies in particular climate regimes (e.g., clouds related to receding Arctic ice in the case of the Barrow ARM site), but have also proved indispensable for climate model evaluation and satellite retrieval validation efforts. The authors have well recognized the history of cloud retrievals in the literature review and properly place their work in the context of previous works. This well written and organized study advances the surface-based cloud remote sensing problem, especially from the high spectral resolution infrared perspective, and should be an interesting and valuable contribution to the atmospheric remote sensing community.

Specific comments:

The study of J. Comstock et al., ‘An inter-comparison of microphysical retrieval algorithms for upper-tropospheric ice clouds’, 2007, Bull. Amer. Met. Soc., should be cited. Although that study focused strictly on cirrus, the lessons gleaned from it are highly applicable to the current study.

Done

p. 8657, 115: Figures 3 and 9 are swapped with each other.

Fixed

The captions appear to be in the correct place, however. Also, Fig. 9 (well, should be Fig. 3) has 862.5 cm^{-1} , but Fig. 2 has 860.5 cm^{-1} . Double-check all wave numbers, their labeling, etc.

Fixed

p. 8658, start of Sect. 2: should also cite Nasiri and Kahn, 2008, J. Appl. Meteor. Climatol., Limitations of bispectral infrared cloud phase determination and potential for improvement.

Done

The authors of this study chose to use windows on either side of the 9.6 micron O₃ band. Why did the authors of the current study choose to use only the 10-12 micron window for phase separation? The 8-10 micron window buys a lot of extra sensitivity. Some additional context to the discussion on p. 8659 in Sect. 2.2 describing the channels used, and why they were chosen, would be beneficial.

In general, we chose from the selection of microwindows found by Mahesh et al. The problem here is that the higher frequency window is less clean, perhaps because water vapor continuum absorption lies closer to its 6.7 micron vibrational mode, such that overlapping Lorentz wings are stronger and good water vapor microwindows are less available.

p. 8659, 119-20: Another useful paper that describes the ability to assess thermodynamic phase in the presence of various degrees of cloud heterogeneity is found in Kahn et al., 2011, JGR, 'Impacts of subpixel cloud heterogeneity on infrared thermodynamic phase assessment. They show that the phase signal is stronger when clouds are more or less homogeneous. When the cloud fields are broken, the phase signal more often appears as unknown. So, in the current work, it is possible that the unknown classification may be a consequence of small-scale heterogeneities in the cloud.

This is an interesting point, but we don't believe that this will be a significant consideration. The AERI horizontal field-of-view is 20 m per kilometer cloud height, so the phase of the cloud would need to change over extremely fine spatial scales.

This also begs the question about time/space sampling of the observations in the current study. Over what time/space windows are individual retrievals obtained? If it was mentioned, it wasn't obvious.

Much of this is in Table 1, but we have also added the following text:

For analysis, measurements were grouped into five minute intervals.

p. 8661, 112-13: This is a very interesting result. Do the authors know if epsilon_p could be significant in other cloud regimes, types, latitudes, etc.? Also, could this be as important for satellite-based retrievals of cloud properties?

No we don't know, although, as a rule of thumb, precipitation proportionate with available cloud condensate. To first order, we would anticipate that the contribution of precipitation to thermal emission is similar.

p. 8662, l4: not a complete sentence. L8-13: it is not immediately clear why the authors spend time obtaining transmissivity in the o3 band, since the cloud retrievals are obtained in the 10-12 micron window. Could the authors clarify this point? Perhaps it is only a matter of connecting one or two dots in some additional description in the right place.

The text has been rewritten to clarify the method. It now reads

In order to constrain estimates of cloud emissivity, it helps to have an estimate of cloud transmissivity t since, to first order, $\epsilon = 1 - t$. Cloud transmissivity is often estimated using the sun as a direct source. The drawback that the sun can be absent for long stretches of time in the Arctic.

Here we estimate cloud transmissivity from the degree to which a cloud attenuates stratospheric ozone emission within a 1038 cm^{-1} to 1042 cm^{-1} microwindow. Because ground based measurements of downwelling radiation include both cloudy emission and ozone transmission, cloudy emission must first be subtracted to obtain the ozone signal. Transmissivity can then be obtained if atmospheric ozone, temperature and moisture profiles are known.

The procedure for estimating cloud transmissivity within the 1038 cm^{-1} to 1042 cm^{-1} microwindow follows a series of steps illustrated in Fig. 8. In the first step, surface radiance measurements $I_{\text{meas}}(\nu)$ are corrected for precipitation emission to give

$$I_{\text{sky}}(\nu) = I_{\text{meas}}(\nu) - \epsilon P(\nu) B(T_p, \nu) \quad (7)$$

In the second step, a wavelength dependent brightness temperature T_{cb} representative of cloud base is estimated from the relation $I_{\text{sky}}(\nu) = B(T_{\text{cb}}, \nu)$. Intensity measurements are evaluated in two ranges, between 960 cm^{-1} and 975 cm^{-1} and between 1070 cm^{-1} and 1085 cm^{-1} . These spectral bands lie within the atmospheric window, but just outside the P and R branches of ozone emission.

In the third step, the prior estimates of brightness temperature from outside the ozone band are used to evaluate values of T_{cb} within the P and R branches associated with ozone emission. This is done using simple linear interpolation. The calculated value of T_{cb} within the ozone band is used to estimate the background radiance from all sources other than ozone and precipitation, $I_{\text{bkg}}(\nu)$.

Fourth, cloud transmissivity t is calculated within the P and R branches of ozone emission. The calculated background emission I_{bkg} is subtracted from measurements of downwelling emission I_{sky} within the P and R branches. The difference is divided by calculated values of the clear sky downwelling radiance I_{clear} in the P and R branches that would be associated with an atmosphere without precipitation or clouds

$$t(\nu) = I_{\text{cloudy}}(\nu) / I_{\text{clear}}(\nu) = (I_{\text{sky}}(\nu) - I_{\text{bkg}}(\nu)) / I_{\text{clear}}(\nu) \quad (8)$$

Values of I_{clear} are estimated using the LBLRTM radiative transfer model and measured profiles of atmospheric ozone, temperature and moisture.

Fifth, values of t that are calculated in two narrower spectral bands – 1020 cm^{-1} to 1040 cm^{-1} in the P branch and 1048 cm^{-1} to 1065 cm^{-1} in the R branch – are then used to interpolate values of t in the Q branch between 1040 cm^{-1} and 1048 cm^{-1} , thereby completing estimates of t within the ozone band. Interpolation is used because ozone emission is weak within the Q branch.

Finally, the desired values of t_{ozone} are obtained from a subset of these ozone transmissivity values, evaluated within a microwindow between 1038 cm^{-1} and 1042 cm^{-1} . This microwindow is chosen because water vapor absorption is particularly small in this band.

L25: briefly describe or reference the minimization approach.

The text now explicitly states that this is a least-squares minimization.

p. 8663, 17-9: Not clear what the authors are describing. Are they suggesting that they have a ‘mixed-phase’ category completely separate from ‘unknown’? Over what spatial and temporal scales is this for? Depending on the instrument resolution (time and horizontal space), or the averaging done before the retrieval is attempted, this will affect the interpretation of these results (see previous comment about phase and heterogeneity).

p. 8667, 118: This appears to be Fig. 3 in the place of Fig. 9.

Fixed

p. 8669: 15-6, ‘having uncertain phase.’ Is this because of the ambiguity in the spectral signature of cloud phase, or because of the previously commented factors about cloud heterogeneity? What about liquid cloud that precipitates ice? Vertical stratification of phases? The reviewer doesn’t expect the authors to address quantitatively all of these questions, but some additional descriptive context is warranted.

The text is now rewritten to state

For clouds with an uncertain phase, retrievals of cloud properties are made assuming that the clouds are liquid. The assumption is that many “uncertain” clouds are in fact mixed-phased, in which case most of the cloud water path (and thermal emission) comes from high concentrations of small liquid droplets (Hobbs and Rangno, 1998). In any case, as will be shown, retrievals tend not to be highly sensitive to this choice.

p. 8669, 19: With regard to the base being warmer than 273 K, isn't it possible that the top of the cloud could be well below freezing, thus ice could be in the cloud? The reviewer realizes this paper is about single layered and geometrically thin cloud. Perhaps the top of the cloud should be above 273 K if the authors are trying to show that there should be no ice occurrences.

Good point. We re-ran the numbers, but they are unchanged. Nonetheless the text is modified to apply to cloud top for this condition.

p. 8669, Fig. 11 discussion. The positive bias of the MWR, is it related to precipitating particles? Is it possible there is a connection between ϵ_p and the positive LWP bias of the MWR?

This is an interesting idea, but we don't think so since precipitation is normally ice phased, which the MWR is insensitive to.

Figs. 4 and 5 would benefit from some color.

Fig. 6 caption: Aqua, not Agua.

Fig. 9, why you no use color? Yucky figure.

Fig. 10: in %?

Fig. 15: need to work on symbols. Might be better to do color dots here. Totally impossible to separate the phase categories apart from each other.

The above are all clarified.