Improving IR cloud phase determination with 20 microns spectral observations

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[1] Adding 20 μm spectral observations to observations in the 8–12 μm region can significantly improve infrared cloud phase determination from both space and the surface. We demonstrate this with 7–20 μm radiance spectra of Arctic stratus clouds measured by a ship-based FTIR spectrometer during the SHEBA experiment. Our results are compared with phase classifications obtained from lidar, microwave radiometer, and radar data. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 9315 Information Related to Geographic Region: Arctic region

1. Introduction

[2] Obtaining reliable cloud thermodynamic phase information is important for remote sensing and for climate modeling purposes. Cloud phase information is a prerequisite for the accurate determination of other cloud properties (temperature, particle size, and condensed water path) from remote sensing observations. Moreover, changes in cloud phase are associated with large changes in radiative fluxes, and cloud precipitation efficiency and lifetime.

[3] Infrared techniques for day- and nighttime remote sensing of cloud phase are founded on the distinct wavelength dependencies of the index of refraction of liquid water and ice. For example, at a wavelength of 8 μm the absorptivities of both phases are about the same, but at 11 μm the absorptivity of ice is much greater than that of liquid water. Contemporary algorithms for the determination of cloud phase from IR observations therefore make use of observations in three channels located at 8, 11 and 12 μm [*Strabala et al.*, 1994], or 3.7, 11 and 12 μm [*Key and Intrieri*, 2000]. Ambiguities with these combinations are encountered for thin clouds, black clouds, or clouds composed of large particles [*Baum et al.*, 2000; *Key and Intrieri*, 2000].

[4] The aim of the present paper is to show that the additional use of spectral radiance measurements at the short wavelength-end of the far-infrared (FIR) spectral region (17–25 μm) can help resolve some of the above ambiguities for IR cloud phase determination. To date, this part of the FIR has only been used in conjunction with the thermal infrared (TIR) for the identification of condensate present in the atmospheres of other planets (e.g., [*Coustenis et al.*, 1999]). For remote sensing of the Earth's atmosphere, it has been considered for the inference of cirrus cloud properties from satellites [*Di Giuseppe and Rizzi*, 1999; *Naud et al.*, 2000] in a manner similar to that envisioned for the submillimeter part of the FIR (140–500 μm) [*Evans et al.*, 1999]. This study is the first where the FIR around 20 μm is employed a) to delineate cloud phase, and b) in the analysis of surface measurements of downwelling IR radiance of Arctic clouds.

2. Theoretical Considerations

[5] An obstacle for broad uses of the FIR is the relative opacity of this spectral region, as compared to the TIR window region. Under some circumstances, however, the Earth's atmosphere can be quite transparent for FIR radiation in small spectral intervals ("microwindows") around 20 μm, between strong water vapor absorption lines. This so-called "dirty window" opens in the cold and dry atmospheres of polar regions and, more generally, above the planetary boundary layer where moisture is concentrated.

[6] In order to demonstrate that signal from low- and mid-level clouds (for which it is relevant to determine phase information) can be sensed in the FIR from the surface and from space, we show in Figure 1 FIR spectra of the e-folding distance of transmission in clear sky standard atmospheres, for upward- and downward-looking observers. The e-folding distance is defined as the vertical distance in the atmosphere from which transmission to the observer is 1/e [*Mahesh et al.*, 2001], and indicates the height where the weighting function peaks at a particular wavelength. Figure 1 reveals that several microwindows existing between 17–24.4 μm (410–590 cm^{-1}) can be incorporated in a spectral analysis of IR cloud observations, because surface and spaceborne radiance measurements in these microwindows will be sensitive to clouds located in the lower troposphere. The four microwindows used in section 3, indicated by triangles in Figure 1, are centered at 17.45, 17.87, 18.81, and 19.14 μm (573.0, 559.75, 531.75, and 522.5 cm^{-1}).

[7] To point out the particular advantage of 20 μm spectral observations for cloud phase discrimination, we have also calculated IR radiance spectra of atmospheres lying over a black surface and containing clouds composed of water droplets and ice with the *Rathke and Fischer* [2000] radiative transfer model. The required cloud spectral optical properties were determined with Mie-theory from the indices of refraction of *Downing and Williams* [1975] and *Warren* [1984] for polydispersions of spherical particles, characterized by a gamma size distribution with effective radius r_{eff} and variance $v_{\text{eff}} = 0.10$. The curves shown in Figure 2 were obtained by converting the radiance spectra to equivalent brightness temperature (BT) spectra, averaging BT over several microwindows (24.4 μm: 406–414 cm^{-1}, 17.9 μm: 558–562 cm^{-1}, 11 μm: 898–906 cm^{-1}, 8.5 μm: 1167–1173 cm^{-1}, 4 μm: 2496–2506 cm^{-1}), and calculating the BT differences from the 11 μm–microwindow. The variation of BT differences with the phase and size of the particles is the physical basis of remote sensing

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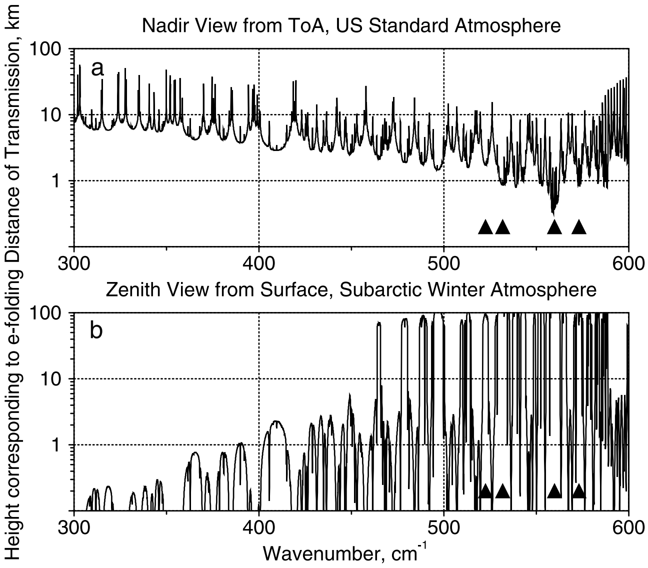

Figure 1. Spectral variation of the height corresponding to the e-folding distance of transmission in the FIR, calculated at a resolution of $\Delta\nu = 0.05$ cm^{-1} with the *Rathke and Fischer* [2000] radiative transfer model, the year 2000 release of the HITRAN database [*Rothman et al.*, 1998], and the CKD2.4 water vapor continuum absorption model [*Tobin et al.*, 1999]. (a) For a nadir view from top-of-atmosphere into a clear US Standard atmosphere (Total Precipitable Water TPW = 1.59 cm). (b) For a zenith view from surface into a clear Subarctic Winter atmosphere (TPW = 0.45 cm). The triangles mark the position of the microwindows included in the spectral analysis (section 3).

algorithms for the inference of these parameters from IR spectral observations. Commonly, measurements made in the TIR or in the solar IR (3–4 μm) atmospheric windows (or a combination of both) are employed (see *Key and Intrieri* [2000], *Rathke and Fischer* [2000], and references therein). However, as demonstrated by Figure 2, the spectral signatures of the liquid and solid phases of water can be separated much better with the help of the FIR.

[8] In fact, as was pointed out by *Naud et al.* [2000] in the context of cirrus particle size estimation, it is a combination of TIR and FIR spectral observations that allows the most accurate retrievals of cloud phase. This distinction is possible because from the TIR to the FIR (and for most particle sizes), liquid water absorption increases, while ice absorption drastically falls off and scattering is more isotropic. These differences follow from the differences between the refractive indices of water and ice and are therefore qualitatively not affected by other choices of ice particle shape and v_{eff}. From the curves of BT(11)–BT(24.4) and BT(11)–BT(17.9) in Figure 2, we infer that the use of the FIR should improve a) satellite remote sensing of the phase of optically thick (black) clouds (which is currently accomplished with cloud top temperature thresholds [*Key and Intrieri*, 2000]), and b) surface remote sensing of the phase of non-black clouds (considering that a water cloud with r_{eff} = 32 μm near cloud base is untypical).

3. Measurements and Data Analysis

[9] The dataset chosen for the present study consists of 83 downwelling IR radiance spectra of stratiform Arctic clouds. They were measured on 22 days from March 8 to April 19, 1998 by the University of Puget Sound Fourier Transform Infrared Spectroradiometer (UPS-FTIR) in the zenith direction from the deck of the Canadian icebreaker *Des Groseilliers*, which was frozen into the Arctic ice pack during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment [*Uttal et al.*, 2002]. The UPS-FTIR is a Bruker IFS-55 spectrometer equipped with two temperature-controlled blackbodies for calibration and external optics for transmitting downwelling radiance into the instrument. The full-angle field-of-view is less than 10°, the spectral resolution is 1.1 cm^{-1}. The detector is a Mercury-Cadmium-Telluride composite with sensitivity greater than 10% of maximum in the range 500–2500 cm^{-1} (4–20 μm). With this spectral range, the UPS-FTIR spectra extend into the FIR. Supplementing this dataset are: a depolarization lidar, a 35 GHz cloud radar, and a microwave radiometer (MWR) [*Shupe et al.*, 2001].

[10] The analysis of the UPS-FTIR's radiance spectra relies on a theoretical model relating cloud microphysical properties (phase,

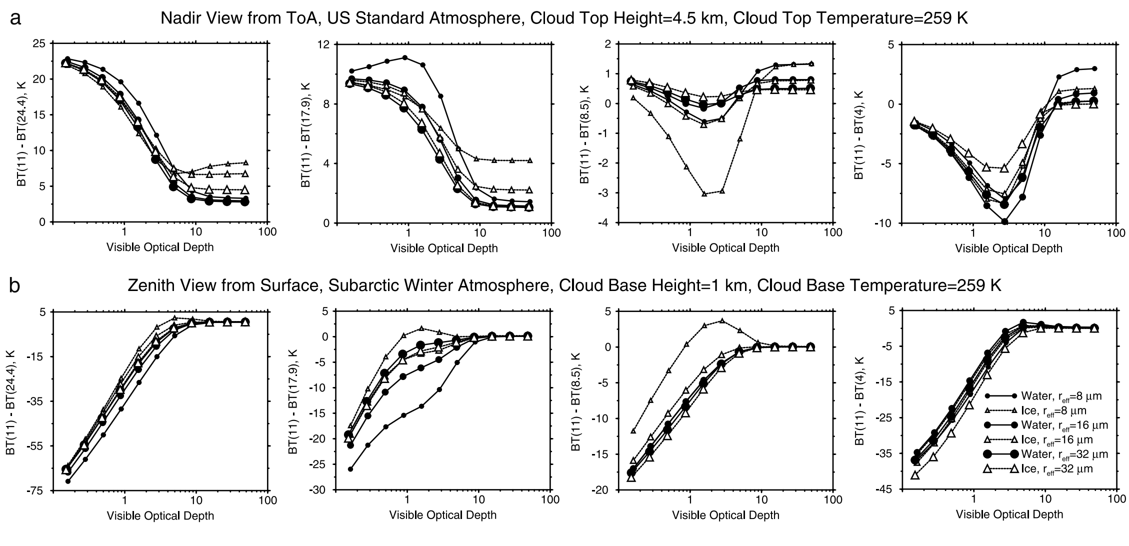

Figure 2. Simulated brightness temperature differences for water (filled circles) and ice clouds (triangles) consisting of spherical particles with different effective radii r_{eff}, as a function of the cloud optical depth at 550 nm. (a) For a nadir view from top-of-atmosphere into a cloudy US Standard atmosphere. (b) For a zenith view from surface into a cloudy Subarctic Winter atmosphere. The BT(11 μm)-BT(4 μm) calculations were done for nighttime conditions. Note the scale changes on the y-axes.

Table 1. Statistics of Case-by-Case Phase Agreement Between FTIR and Other Instruments

	MWR	MWR + radar	lidar	MWR or radar or lidar[a]
TIR only	17%	31%	13%	23%
TIR + FIR	66%	71%	56%	70%
Samples[b]	83	45	39	83

[a] Agreement with the phase information of at least one instrument.
[b] Data outages for the lidar, cases where the lidar signal didn't attenuate in the lowest cloud layer, and cases of "mixed-phase" clouds were not considered.

r_{eff}, and condensed water path) to cloud IR spectral optical properties (optical depth, single-scattering albedo, and asymmetry factor of the phase function). These parameters are input, together with radiosonde temperature and humidity profiles, to a radiative transfer model which calculates a radiance spectrum. An algorithm then finds the cloud microphysical properties and the cloud height for which the simulation best reproduces the measured radiance in a least-squared sense. Here, we employed two variants of the *Rathke and Fischer* [2000] algorithm. The first, the "TIR only" version, takes into account radiance in microwindows located between 786–1233 cm^{-1} for the determination of the cloud microphysical properties, and radiance in CO_2 absorption channels located between 700–740 cm^{-1} for inferring cloud height (after *Mahesh et al.* [2001]). The second, or "TIR + FIR" version, is identical yet additionally includes radiance in the four FIR microwindows described in section 2 and in CO_2 absorption channels located between 590–630 cm^{-1}. Our analysis is not affected by the lower sensitivity of the MCT detector in the FIR because the BT differences between water and ice clouds are large in this spectral region (BT(11)–BT(17.9) > 2 K, see Figure 2). Having these two versions allowed us to study the influence of the considered spectral ranges on the final products of the spectral analysis.

4. Results and Discussion

[11] Each radiance spectrum in the dataset was analyzed according to the two algorithms described above. To measure the mutual consistency of the two methods, we calculated the linear correlation coefficient, r, for each retrieved property; each value of r was based on all 83 pairs of retrieved values. The poorest correlation occurred for retrieved phase, with $r = 0.04$. In order to exclude this effect from correlations of other properties, subsequent comparisons were made for retrievals in which the phase was assumed to be entirely liquid or entirely ice. The correlation coefficients of base height using these constrained retrievals were $r = 0.77$ (liquid) and $r = 0.54$ (ice). For effective radius we obtained $r = 0.89$ (liquid) and $r = 0.38$ (ice). For condensed water path, we obtained $r = 0.92$ (liquid) and $r = 0.48$ (ice). Our interpretation of these results is that FIR radiance contributes decisively to the discrimination of phase. For other retrieved products, the contribution of FIR radiance is still important, but not as much as for phase.

[12] With measurements of cloud layer average lidar depolarization ratios (γ), the MWR-derived total column liquid water path (LWP), and height-resolved measurements of radar reflectivity and Doppler velocity, we independently classified the lowest cloud layer phase as "all-liquid" ($\gamma \leq 0.11$ or LWP > 0 and specific radar return), "all-ice" ($\gamma > 0.16$ or LWP = 0), or "mixed-phase" ($0.11 < \gamma \leq 0.16$ or LWP > 0 and specific radar return). These classifications make a physical interpretation of the cloud phase determined from the downwelling IR radiance measurements possible. A validation of the cloud phase product is, strictly speaking, not feasible, because the individual instruments, depending on their wavelengths of detection, have different sensitivities to large (radar) or small (lidar, FTIR) particles and to the liquid phase (MWR). Nevertheless, Table 1 demonstrates that accounting for the FIR measurements of the UPS-FTIR leads to individual phase retrievals agreeing much better with indications from the lidar, radar and MWR.

[13] To illustrate where differences to the "TIR only" version originate, Figure 3 shows one example of a cloud radiance spectrum measured by the UPS-FTIR for which unambiguous cloud phase determination is only possible in the FIR. In this case, the "TIR only" version of the analysis technique retrieved an ice phase, but the true phase was all-liquid, according to the lidar, radar, and MWR.

[14] The frequency of occurrence of the different cloud phases as a function of cloud temperature (T_{cloud}, inferred with the "TIR + FIR" version of the spectral method from the UPS-FTIR observations) is shown in Figure 4 for the 83 considered cases. In order to get meaningful statistics the samples were separated into two groups (each containing ~40 samples) distinguished by T_{cloud} above and below −17°C. The accuracy of the cloud base height and temperature product has already been evaluated (C. Rathke et al., Multi-angle downwelling infrared radiance of Arctic stratus clouds, submitted to the *Journal of Geophysical Research*, 2001), and it was shown that the retrieved T_{cloud} is close to its ambient, in-cloud value.

[15] Also shown in Figure 4 is the frequency of appearance of cloud phase as a function of cloud ambient temperature, compiled by *Matveev* [1984] from in-situ aircraft measurements made over the former USSR. This climatology is employed for temperature-

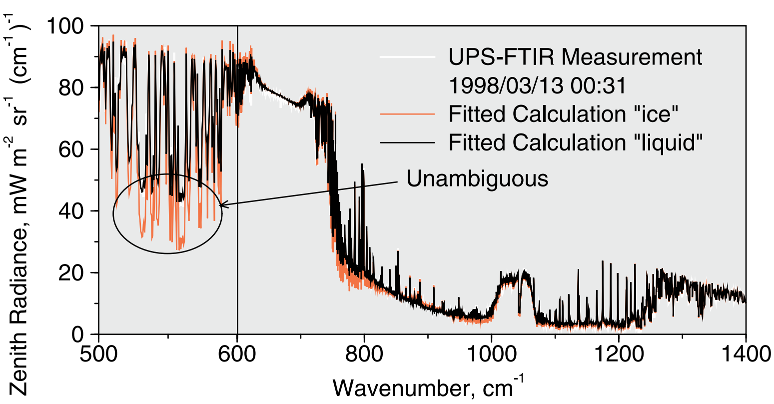

Figure 3. Measured IR cloud radiance spectrum, overlaid with the best fit simulated ice cloud and liquid water cloud spectra resulting from the spectral analysis. In this case, unambiguous cloud phase determination is only possible in the FIR.

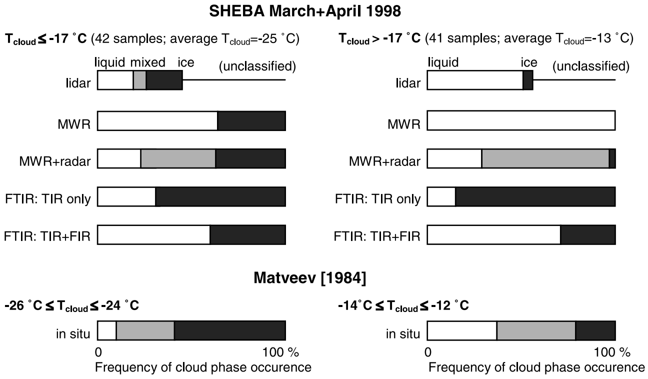

Figure 4. Frequency of cloud phase occurrence retrieved from data of the lidar, MWR, radar, and UPS-FTIR operating at the SHEBA site from March to April 1998, as a function of two cloud temperature intervals (unclassified cases are data outages for the lidar and cases where the lidar signal didn't attenuate in the lowest cloud layer). Statistics reported by *Matveev* [1984] are also shown for comparison.

dependent partitioning of cloud phase in climate models [*Roeckner et al.*, 1996] and to check results of prognostic bulk microphysical schemes [*Del Genio et al.*, 1996].

[16] Due to the frequent occurrence of mixed-phase clouds, the information provided by the four instruments leads to different cloud phase statistics. However, the TIR+FIR retrieval does a better job of capturing both the cloud phase statistics derived from the lidar, MWR and radar data, and the trend of increasing liquid water with temperature. Interestingly, Figure 4 indicates that the clouds sampled by the UPS-FTIR during March–April 1998 at the SHEBA site were more often liquid than expected for their temperature range according to *Matveev* [1984].

5. Conclusions

[17] Our results demonstrate that accounting for the information contained in the 20 μm spectral range is decisive for the purpose of discriminating cloud phase with IR radiance spectra. Use of the extended range leads to cloud phase statistics in much better agreement with classifications made by other instruments. Moreover, as the cloud phase retrieved from TIR + FIR observations is the "radiatively relevant" cloud phase for the longwave spectral region, having accurate statistics of this quantity is helpful for energy budget calculations.

[18] We expect that cloud phase determination from above (i.e. from satellite or aircraft) can also be improved with 20 μm spectral observations, especially for optically thick cloud layers. However, since the pair of Infrared Interferometer Spectrometers (IRIS-B and −D) flown in 1969–1971 [*Hanel et al.*, 1971], no satellite instruments have had channels in both the TIR and the FIR. Therefore, demonstrating the general benefit of cloud observations extending into the FIR spectral region will only be possible with future measurements by, for example, the Tropospheric Airborne Fourier-Transform Spectrometer (TAFTS) [*Caas et al.*, 1997] or the Radiation Explorer for the Far Infrared (REFIR) [*Rizzi et al.*, 1998].

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