Microphysical Properties of Single and Mixed-Phase Arctic Clouds Derived from AERI Observations

D. D. Turner
University of Wisconsin-Madison
Madison, Wisconsin
and
Pacific Northwest National Laboratory
Richland, Washington

Abstract

A novel new approach to retrieve cloud microphysical properties from mixed-phase clouds is presented. This algorithm retrieves cloud optical depth, ice fraction, and the effective size of the water and ice particles from ground-based, high-resolution infrared radiance observations. The theoretical basis is that the absorption coefficient of ice is stronger than that of liquid water from 10 μm to 13 μm, whereas liquid water is more absorbing than ice from 16 μm to 25 μm. However, due to strong absorption in the rotational water vapor absorption band, the 16 μm to 25 μm spectral region becomes opaque for significant water vapor burdens (i.e., for precipitable water vapor amounts over approximately 1 cm). The Arctic is characterized by its dry and cold atmosphere, as well as a preponderance of mixed-phase clouds, and thus this approach is applicable to Arctic clouds. Since this approach uses infrared observations, cloud properties are retrieved at night and during the long polar wintertime period.

The analysis of the cloud properties retrieved during a 7-month period during the Surface Heat Budget of the Arctic (SHEBA) experiment demonstrates many interesting features. These results show a dependence of the optical depth on cloud phase, differences in the mode radius of the water droplets in liquid-only and mid-phase clouds, a lack of temperature dependence in the ice fraction for temperatures above 240 K, seasonal trends in the optical depth with the clouds being thinner in winter and becoming more optically thick in the late spring, and a seasonal trend in the effective size of the water droplets in liquid-only and mixed-phase clouds that is most likely related to aerosol concentration.

Introduction

The Arctic serves as the heat sink for the global climate system, as to first order the energy budget of the Arctic is a balance between infrared emission to space and the energy transport from the mid-latitudes (Nakamura and Oort 1988). Clouds significantly modulate the radiative fields and errors in the cloud properties can result in significant errors in the modeled radiative flux at the surface and top of the atmosphere, as well as the radiative heating rate profile of the atmosphere. The radiative effect of a cloud depends on its macrophysical (height, vertical extent, horizontal cloud fraction, etc.) and microphysical (phase, particle size, etc.) properties.

One of the primary unknowns is the phase of Arctic clouds (Curry et al. 1996). The degree to which the radiation is modulated depends on the thermodynamic phase, size, shape, and density of the cloud particles, as these dictate the single scattering properties of the particles. Determining the phase of the cloud particles (i.e., whether they are liquid water or ice) is a prerequisite to specifying the optical properties, as an incorrect phase assessment can lead to errors in the estimates of the single scattering properties. These errors lead to errors in the modeled radiative flux. For example, an incorrect determination of cloud phase can result in large (20%-100%) errors in the effective radius of the cloud particles and optical depth, which translate into errors in the downwelling longwave and shortwave fluxes of 5% to 20% (Key and Intrieri 2000).

A novel new technique is presented which retrieves microphysical cloud properties from ground-based radiance observations made by the Atmospheric Emitted Radiance Interferometer (AERI). This technique was applied to data collected during the SHEBA experiment. This algorithm can also be applied to data collected from 1998 to the present at the Atmospheric Radiation Measurement (ARM) site in Barrow, Alaska, thus provide the long-term data sets required to understand the seasonal nature of Arctic clouds and their interactions with the surface and surrounding atmosphere, as well as for satellite validation.

Retrieval Algorithm

There are several techniques that retrieve cloud phase from passive remote sensing observations (e.g., Key and Intrieri 2000). These techniques take advantage of the changes in the refractive indices of ice and water as a function of wavelength. To unambiguously determine phase from passive remote sensing data, observations should be made in spectral regions where the absorption coefficient of ice and water ‘flips’ with respect to each other; i.e., ice is more absorbing than water at some wavelengths and less than that of water at others. Two examples of retrievals that take advantage of this technique are (Daniel et al. 2002; Turner et al. 2003); however, the former uses data from 850 nm to 1050 nm and thus is not applicable during the nighttime periods or the polar winter while the latter uses infrared observation. Figure 1 shows the wavelength dependence of the absorption coefficient of ice and water in the infrared, along with a typical clear-sky brightness temperature spectrum observed by the AERI at SHEBA.

The observations from 16 μm to 25 μm (400 to 600 cm^{-1}) are critical for unambiguous phase determination. As illustrated in Figure 2, it is possible to find ice and water clouds with similar optical depth and particle sizes that yield almost identical downwelling radiance signatures from 8 μm to 13 μm (750 to 1250 cm^{-1}). However, there are significant differences in the 16 μm to 25 μm observations that allow the cloud phase to be identified. A simple threshold-based approach has been developed to determine cloud phase from AERI observations when the precipitable water vapor (PWV) is less than approximately 1 cm (Turner et al. 2003).

Building upon this threshold-based algorithm, a physical retrieval was developed using the optimal estimation approach to retrieve microphysical cloud properties from Arctic clouds (Turner 2003). The algorithm retrieves cloud optical depth at 900 cm^{-1} (τ), ice fraction (f_i), and the effective radii of the water ($r_{e,w}$) and ice ($r_{e,i}$) particles. An example of the retrieval is presented for March 8, 1998, during SHEBA in Figure 3. Collocated depolarization aerosol and backscatter unattended lidar (DABUL) data

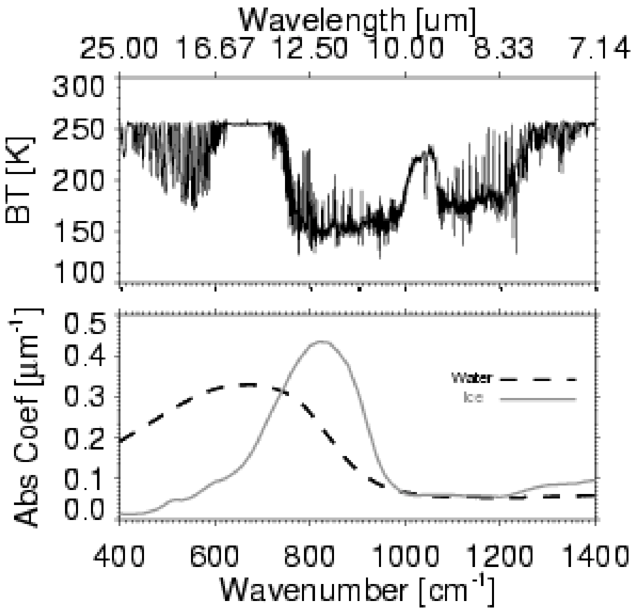

Figure 1. Observed brightness temperature spectrum by the AERI on 4/25/98 at SHEBA (top) and the absorption coefficients of ice and water.

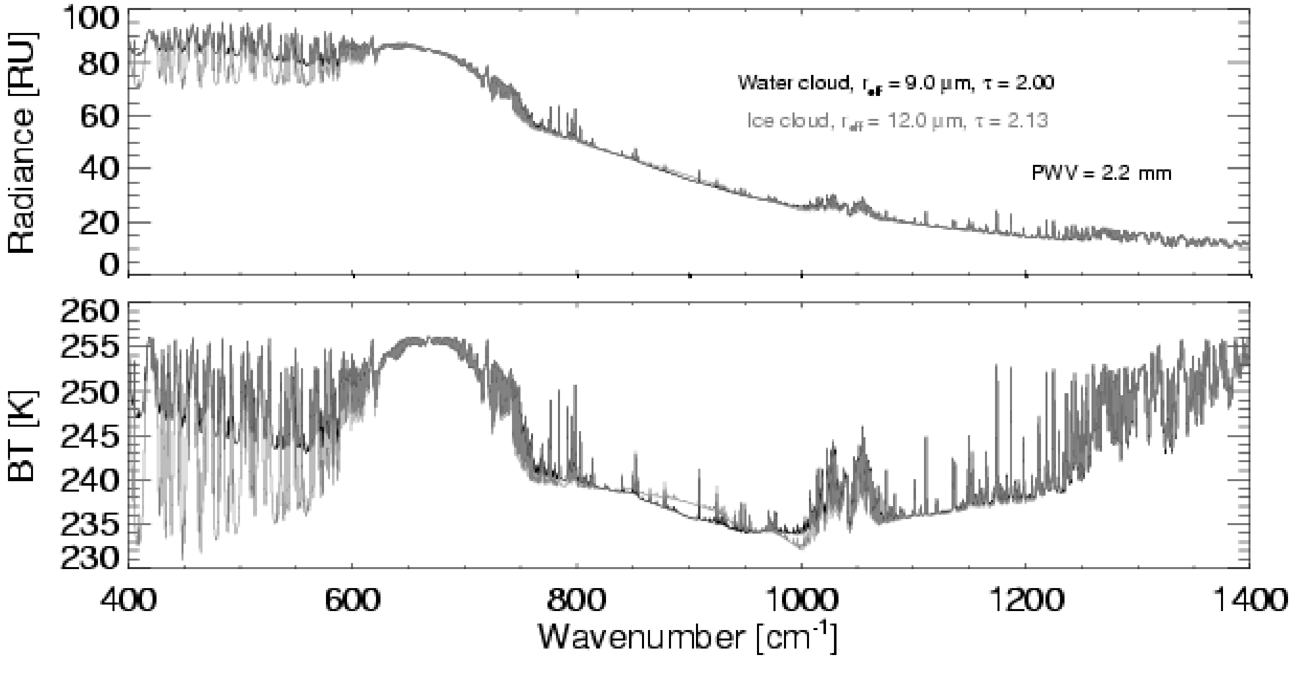

Figure 2. Downwelling radiance (top) and brightness temperature (bottom) spectra for an ice and water cloud demonstrating that unambiguous phase determination in the infrared requires observations in the 400 to 600 cm^{-1} region.

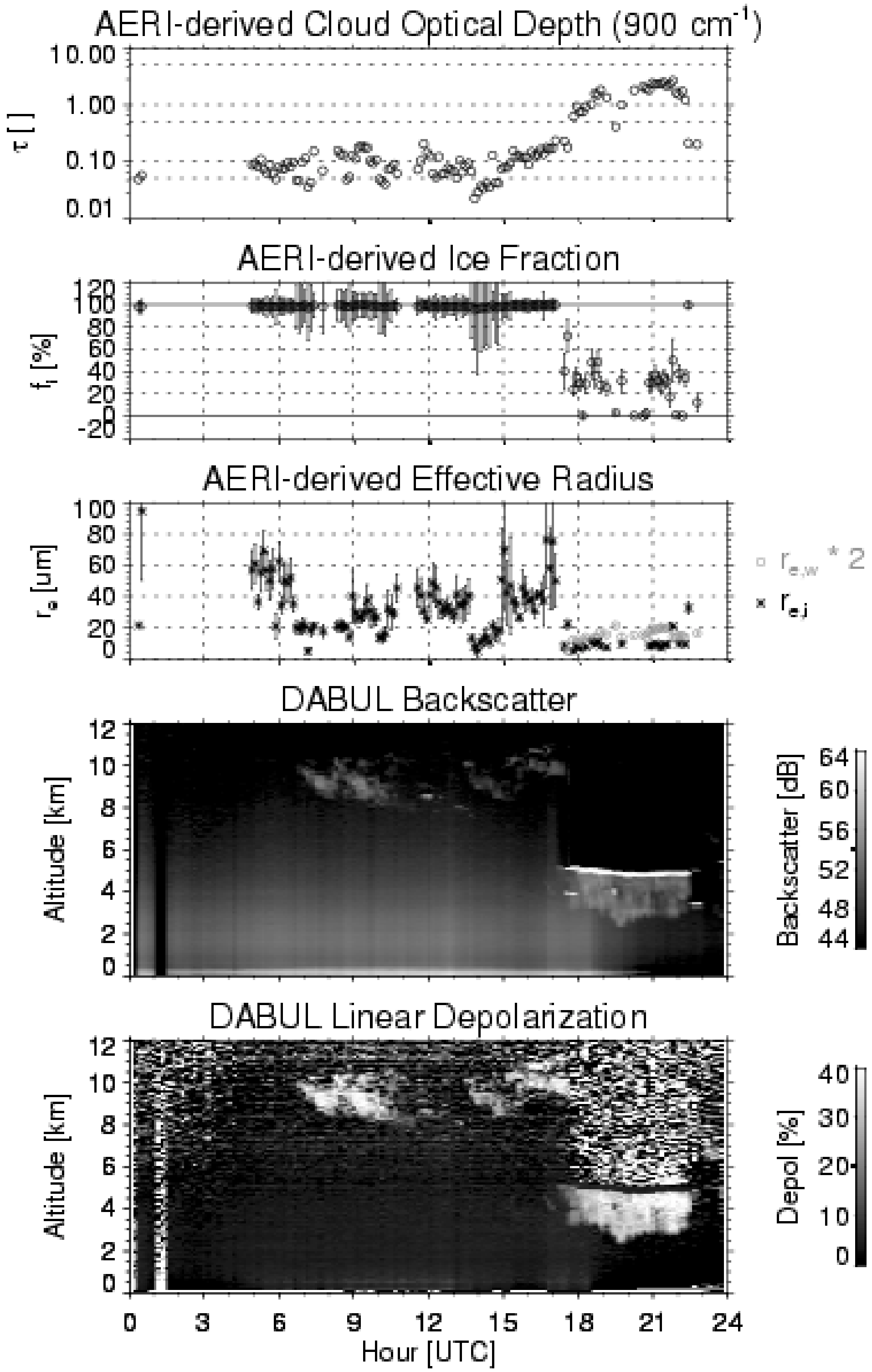

Figure 3. AERI retrievals for March 8, 1998, over SHEBA, with collocated DABUL observations.

(a polarization-sensitive cloud lidar developed by National Oceanic and Atmospheric Administration [NOAA] Environmental Technology Laboratory [Alvarez et al. 1998]) show a thin cirrus layer from approximately 0600-1800 UTC and a mid-level liquid-water cloud that is precipitating ice from 1800 to 2300 Universal Time Coordinates (UTC). The AERI retrievals show that the cirrus cloud is optically thin ($\tau < 0.2$), an ice fraction of 1 (all ice), and $r_{e,i}$ values that range from 20 μm to 60 μm. The mid-level cloud is optically thicker ($0.5 < \tau < 3$), the ice fraction ranges from 0 (all liquid) to 0.5, the water droplets grow from $r_{e,w}$ = 5 μm to 10 μm over the 5 h period, and the $r_{e,i}$ values range from 10 μm to 15 μm.

Uncertainties in the AERI observations, cloud temperature, and water vapor are propagated into uncertainties in the retrieved parameters. The uncertainties in the observations have different effects on the retrieved results. For example, uncertainties in cloud temperature primarily effect only the optical depth, while uncertainties in PWV impact the accuracy of the retrieved ice fraction. The AERI instrument noise is not an issue for clouds with $\tau > 0.5$.

Results from SHEBA

An AERI was deployed as part of the SHEBA experiment from October 1997 – September 1998. During this period, the AERI and the DABUL (which is used with radiosonde profiles to estimate cloud temperature) operated normally between November through May. These results only include periods where the clouds are either single-layer or have a maximum separation of less than 2 km, and have an emissivity of between 0.05 and 0.95 at 900 cm^{-1}. Clouds were considered liquid-only if $f_i < 20\%$, ice-only if $f_i > 80\%$; otherwise the cloud was considered mixed-phase. For each class of clouds, the distribution of τ, $r_{e,w}$, and $r_{e,i}$ was computed. Single-phase clouds demonstrate larger range for τ with significant numbers of clouds with $\tau < 1$, whereas mixed-phase clouds tend to have optical depths near the upper limit of the AERI (cloud emissivity of 0.95 at 900 cm^{-1} translates into an optical depth of approximately 5). The $r_{e,w}$ results for water-only clouds have a mode radius of 9 μm and significant numbers of larger droplets. However, the $r_{e,w}$ data for mixed-phase clouds show a significantly smaller mode radius (7 μm) and fewer larger sizes. The most likely explanation is preferential freezing of the larger droplets in mixed-phase clouds, which removes them from the size distribution resulting in a smaller effective radius. The values for $r_{e,i}$ for ice-only clouds show a mode radius of 25 μm with a fair number of larger effective radii; however, the $r_{e,i}$ values for mixed-phase clouds show a significantly smaller effective radius. There is large uncertainty in the retrieved $r_{e,i}$ values for mixed-phase clouds when $\tau \sim 3$, but simulations show that the other retrieved parameters (τ, f_i, and $r_{e,w}$) are fairly accurate in these conditions. Therefore, the retrieved $r_{e,i}$ distribution for mixed-phase clouds has a very large uncertainty associated with it. These data also demonstrate a lack of temperature dependence in the ice fraction for cloud temperatures above 240 K. Monthly analysis shows seasonal trends in the optical depth with clouds being thinner in winter and more optically thick in the late spring. The data also show a seasonal trend in the effective size of the water droplets in liquid-only and mixed-phase clouds that is most likely related to aerosol concentration.

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Corresponding Author

D. D. Turner, dave.turner@pnl.gov

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