The Characterization of Arctic Mixed-Phase Cloudy Boundary Layers: A Case Study

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1. Introduction

Radiative cloud forcing is an important component of the Arctic climate, with Arctic clouds primarily warming the surface (e.g., Intrieri et al. 2002). Recent decades have seen a rapid warming of the Arctic surface (Stone, 1997; Bradley et al., 1993), and an improved understanding of Arctic cloud optical properties is critical if we are to understand and predict Arctic climate change.

One important observation from the Surface Heat Budget of the Arctic experiment (SHEBA) is that most Arctic clouds contain both liquid and ice somewhere within the vertical column (Shupe et al., 2001). Clouds with liquid water can substantially increase the measured surface infrared flux, especially during the winter months (Intrieri and Shupe, 2002). Even small amounts of liquid water within ice clouds are radiatively important (e.g., Hogan et al. 2002).

Such clouds, because they contain two phases, are generally difficult to characterize using current remote sensors and retrievals.

For a long-lived mixed-phase cloud with often high liquid water paths existing from May 1 - May 10, 1998 at the SHEBA site, a separate, vertically-resolved characterization of the liquid and ice components can be done using a combination of different sensors.

2. Approach

Ice cloud properties are derived solely from 35-GHz radar reflectivities and mean reflectivity-weighted Doppler velocities (Matrosov et al., 2002 with updated coefficients in Matrosov et al., 2003; hereafter M02).

Liquid profiles are derived by:
- using lidar to establish the cloud base
- determining the adiabatic profile corresponding to the lidar cloud base
- constraining the adiabatic profile with the microwave-derived liquid water path
- deriving a liquid extinction coefficient using an assumed cloud droplet concentration of 60 per cc, consistent with liquid-only cloud retrievals (Shupe et al., 2001)

Liquid profiles are established whenever lidar data is present and a non-zero microwave-derived liquid water path exists.

Both liquid and ice extinction coefficient profiles established at a 10-minute time resolution.

Insitu data is used to increase confidence in both the liquid and ice remotely-determined vertical profiles

On May 4, the NCAR plane flew over the SHEBA site. The aircraft flight path is shown projected upon the radar spectral width in Doppler velocities whenever it is within 10 km of the SHEBA ship; darker colors indicate closer proximity. The lidar cloud base is shown as black dots. The liquid water contents measured during the aircraft ascent at 23:18-23:21 were compared to the remote retrieval. Ice mean microphysical quantities calculated during the horizontal overpasses of the SHEBA site between 23:18-24:15 were compared to radar-retrieved quantities.

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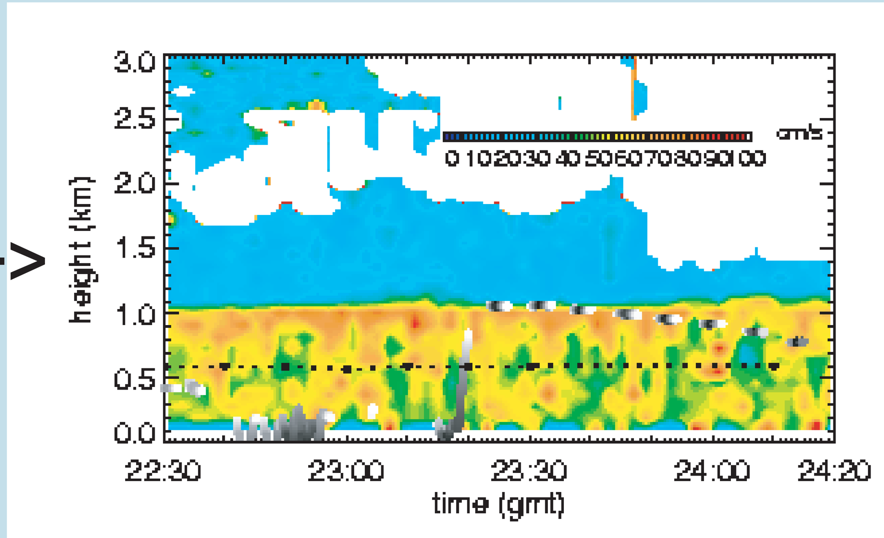
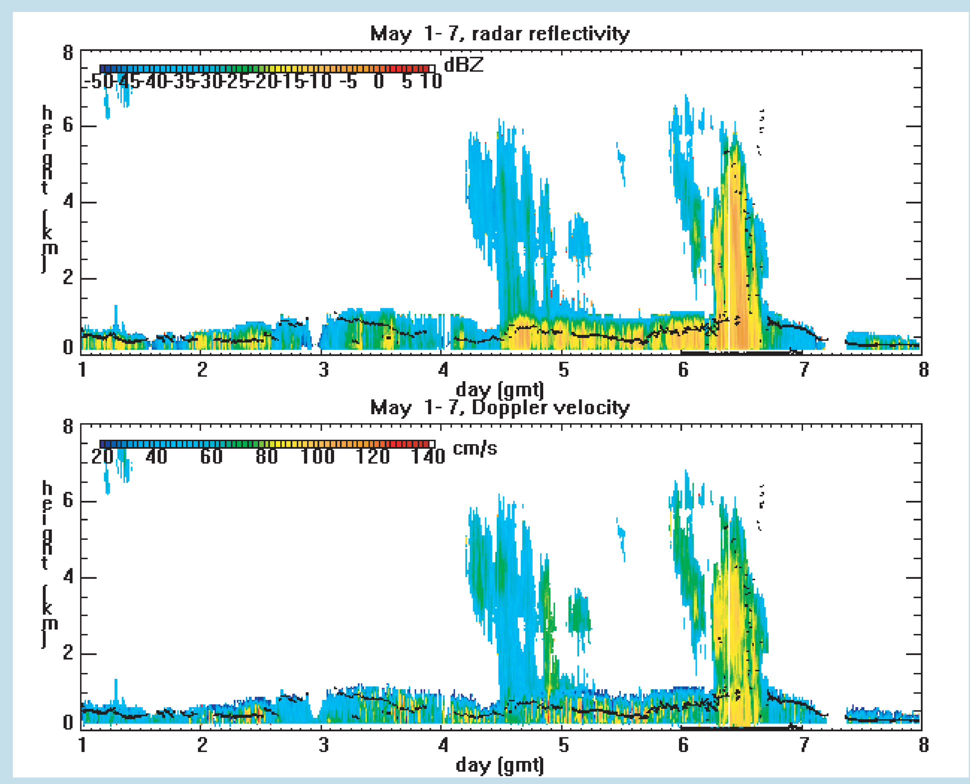


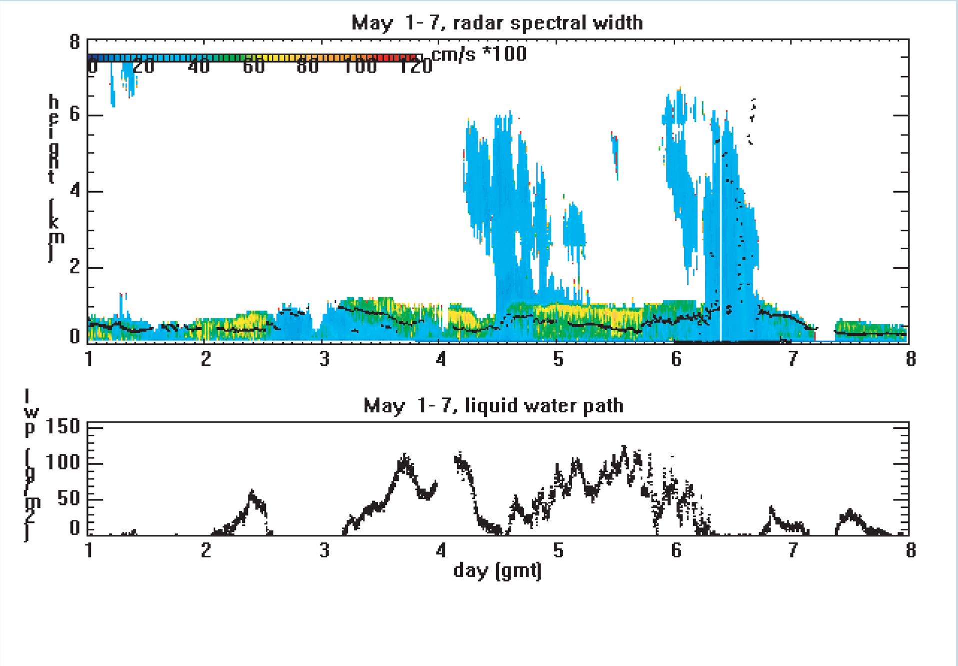
A temperature inversion of 2-3 K was almost consistently present during May1-10, even during the presence of the two upper clouds. The radar-determined cloud top agreed with the location of the temperature inversion.

3. May 1-10 Case Study

A low cloud persisted and two upper clouds came and went. The radar, lidar, microwave, and sonde measurements show the lower cloud usually contained both ice and super-cooled (T ~ -21 degrees Celsius) liquid. The upper clouds were ice only. During the first high cloud on May 4th, the lower liquid layer initially depleted but then reestablished itself. The May 6th high cloud contained higher radar reflectivities and ice water contents, and appears to foster the complete depletion of the lower super-cooled liquid layer.



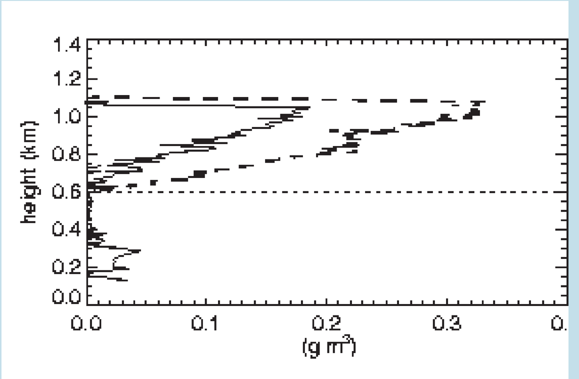
High radar reflectivities (> ~ -30 dBZ) and high doppler velocities (> ~ 60 cm/s) can indicate the presence of ice in non-precipitating clouds. Black dots show lidar-determined water cloud base(s).



High values (> ~0.4 cm/s) of the spectral width in the doppler velocities can indicate the presence of both liquid and ice, with the ice falling much faster than the liquid particles. Low spectral width values are more indicative of single-phase, either ice or liquid, conditions. The lower panel shows the microwave-derived liquid water path.

4. Comparison of liquid and ice remote retrievals to insitu measurements

a) liquid water contents

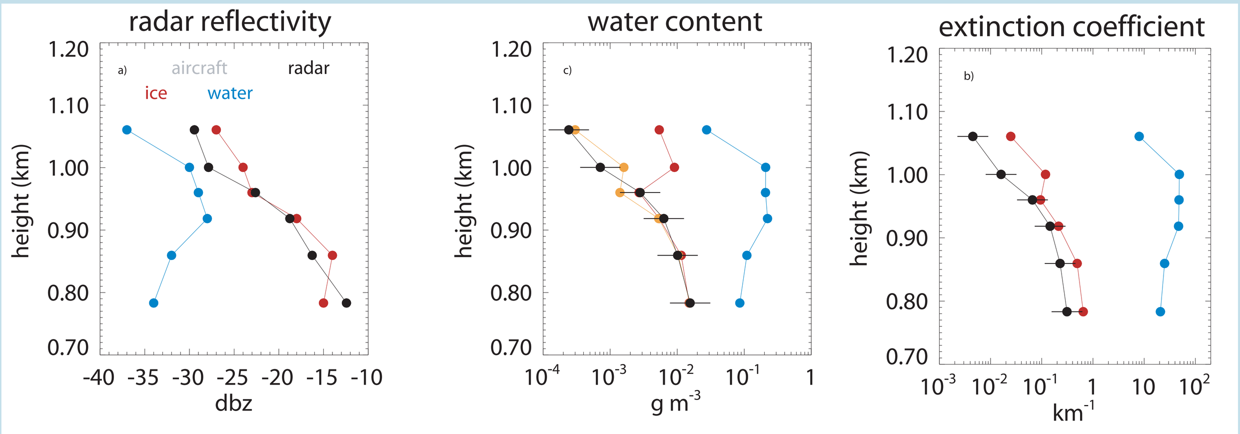


The aircraft detected one adiabatically-distributed liquid layer (solid line). The lidar-determined cloud base (lidar depolarization ratio <0.11; dotted line) agrees with the aircraft-sensed liquid cloud base. The remotely-retrieved liquid water content values (dashed line) are higher than the aircraft values, and are thought to reflect different vertical sampling.

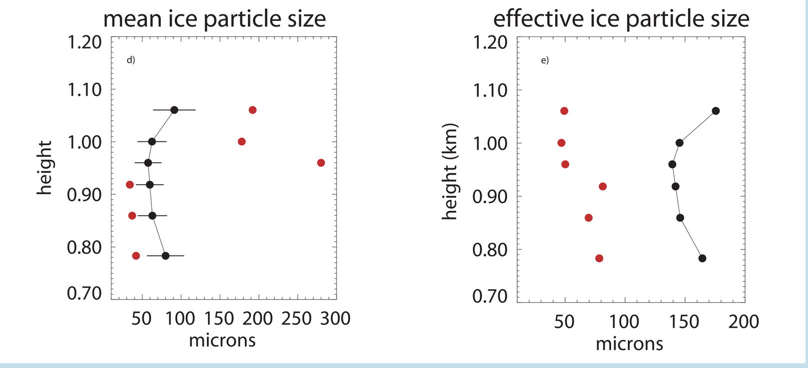
b) ice

Aircraft Ice water content (IWC) and radar reflectivity calculations assume a density that decreases with particle size (Locatelli and Hobbs, 1974; Brown and Francis 1995) consistent with the M02 methodology. Another IWC calculation accounts for particle area and perimeter as well as particle length and width (Baker et al., 2002). The aircraft and radar-retrieved higher-order moments of the particle size distribution (reflectivity and IWC) compare well to each other, despite the large liquid component of the cloud. This helps validate the extension of the M02 technique to mixed-phase conditions

black=radar red=aircraft ice, CPI and 260X blue=aircraft liquid, CPI and FSSP *
yellow=Baker et al. 2002 technique



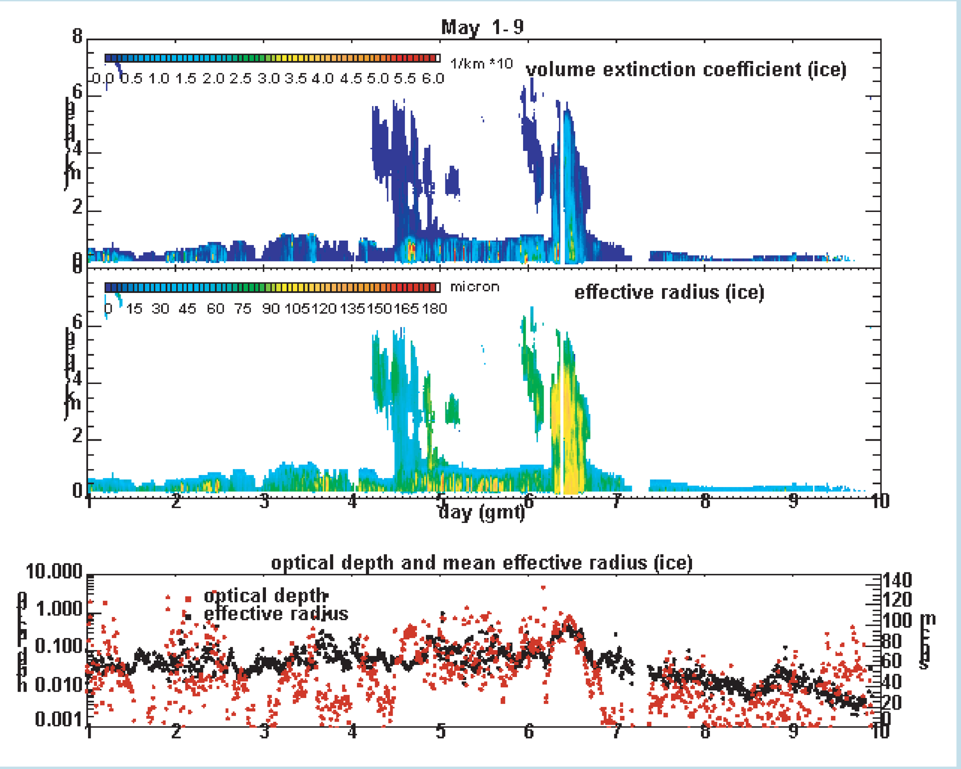
Radar retrievals of the lower-order moments (volume extinction coefficient, mean and effective particle size) differ by about a factor of two from the aircraft values. Effective particle size is derived as Deff= 1.5 IWC/(ρ*projected area); projected area =0.5*volume extinction coefficient, ρ = 0.917 g/cc

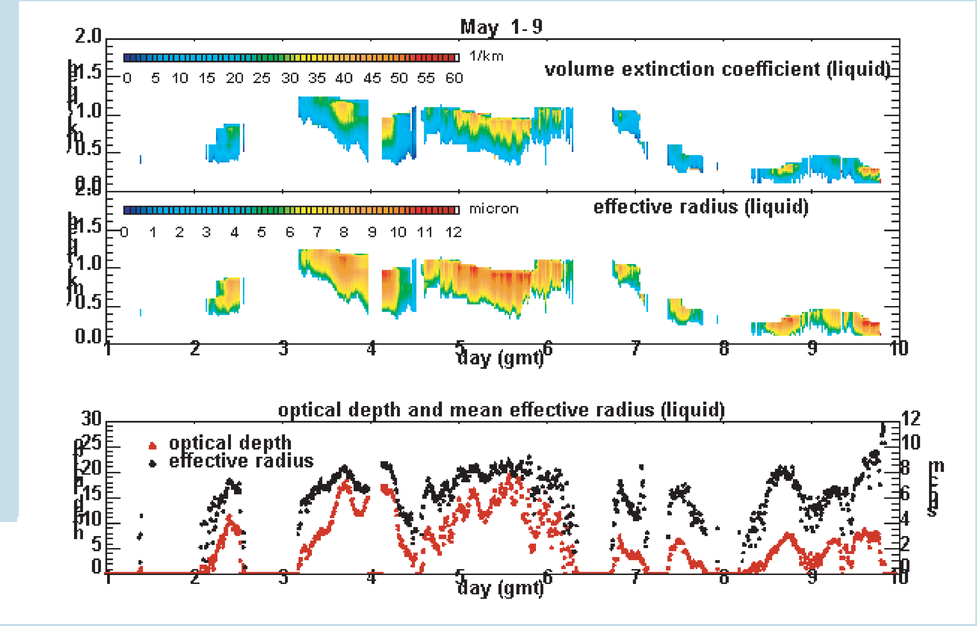


The small particle population may not be adequately represented by the exponential particle size distribution utilized within the radar retrieval, primarily affecting the lower-order moments. The aircraft particle sizes reflect two separate and simultaneous ice formation mechanisms, with large particles seeding the cloud from above, and local ice formation from large liquid drops.

* CPI = Cloud Particle Imager
FSSP = Forward scattering spectrometer probe - 100
260X = 1D optical array probe- 260 X

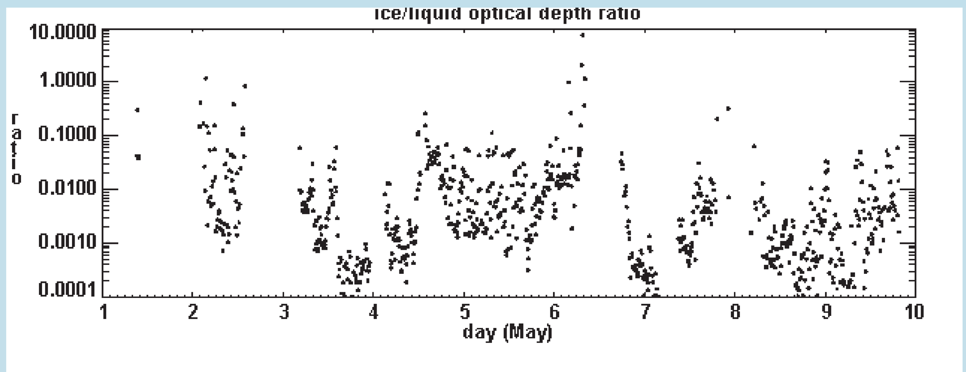
5. Liquid and Ice Extinction Coefficients and Optical Depths





Note different vertical scale from above

The liquid optical depth far surpasses the ice cloud optical depth. The main but indirect radiative influence of the ice is its depletion of the liquid layer on May 6th. Note the increased ice extinction values within the lower cloud at times when upper clouds are present.



6.Conclusions

The M02 technique is shown to perform well for retrieving IWC within mixed-phase cloud, even with high liquid water contents. The technique appears to underestimate the volume extinction coefficient and overestimate mean and effective particle sizes. This is hypothesized to reflect an inadequate modeling of the small particle population by an exponential distribution.

Calculations of IWC also using particle area and perimeter Baker et al. (2002) may perform better at low IWCs (and large particle sizes) than a method using only particle length and width along with the density-size relationship of Brown and Francis (1995).

Aircraft observations confirm the assumption, central to the multi-sensor retrieval of the liquid component, of one, adiabatically-distributed liquid layer.

The separate characterization by phase confirms that almost all of the cloud optical depth is from the liquid component. Large decreases in cloud optical depth accompany the presence of upper ice clouds, consistent with cloud seeding from above.

For clouds with liquid water paths < 25 g/m*m a different characterization of the liquid component is needed (Westwater et al., 2001). Future work will examine other FIRE.ACE mixed-phase clouds.

References: Baker, B., C. Schmitt, P. Lawson, and D. Mitchell, 2002: Further analysis and improvements of ice crystal mass-size relationships. 11th AMS Conf. on Cloud Physics, 3-7 June, Ogden, UT.
Matrosov, S. A.V. Korolev, and A. J. Heymsfield, 2002: Profiling cloud ice mass and particle characteristic size from Doppler radar measurements. J. Atmos. Ocean. Tech., 19, 1003-1018.
Matrosov, S.Y. , M. D. Shupe, A.J. Heymsfield, P. Zuidema, 2003: Ice cloud optical thickness and extinction estimates from radar measurements. submitted to J. Appl. Met.

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