An Annual Cycle of Arctic Cloud Microphysics

M. D. Shupe
Science and Technology Corporation
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

T. Uttal
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

S. Y. Matrosov
Cooperative Institute for Research
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

Introduction

Clouds are important in determining the radiative balance of the earth's atmosphere, particularly in the Arctic where there are low temperatures, low atmospheric moisture, and highly reflective ice/snow-covered surfaces. Several studies have demonstrated the importance of specific cloud microphysical properties on cloud-radiation and ice-albedo feedback mechanisms; these in turn have a bearing on sea-ice thickness and the onset/length of the melt season (e.g., Curry and Ebert 1992; Zhang et al. 1996). Profiles of a priori cloud microphysical properties can also be used to calculate more accurate atmospheric heating rate profiles than those that are typically calculated with bulk cloud parameterizations.

In spite of the importance of clouds in the Arctic environment, both global climate models and more focused single-column models (SCMs) have difficulty specifying and handling clouds. A comparison of many global climate models showed that even cloud fraction results in the Arctic are highly uncertain and significantly impact other modeled parameters (Tao et al. 1996). Morrison et al. (2002) demonstrated that an Arctic-specific SCM that contains detailed cloud microphysical processes still has difficulty partitioning cloud phases. To address these modeling issues, more cloud data, including realistic fields of cloud microphysics, is needed.

This paper presents an annual cycle of cloud microphysics derived from radar, microwave, and infrared radiometer measurements. These instruments were operated for one year during the Surface Heat Budget of the Arctic Ocean (SHEBA) field project (Uttal et al. 2002) deployed at a ship-supported ice camp in the Beaufort and Chukchi Seas north of Alaska during 1997-1998. Results presented here are an extension of the four-month cloud analysis given by Shupe et al. (2001). The framework used to produce the SHEBA cloud dataset is currently being applied to similar measurements from the ARM North Slope of Alaska (NSA) site—producing more than two years of cloud microphysics data at that site to date.

Instruments and Techniques

A suite of retrieval techniques (three for ice clouds and three for water clouds) has been developed to accommodate the variable cloud scenes that are encountered in the Arctic. The retrieval techniques are based primarily on 35-GHz radar reflectivity and/or Doppler velocity measurements. A dual-channel Microwave Radiometer (MWR), measuring brightness temperatures at 23.8 and 31.4 GHz, provides estimates of the column integrated liquid water path (LWP), which is used to constrain one liquid cloud retrieval technique. An Atmospheric Emitted Radiance Interferometer (AERI), measuring spectral infrared radiances from 3-20 μm, also provides an optical depth constraint on one of the three ice cloud retrieval techniques. Both of these radiometers were operated by ARM at SHEBA. A depolarization lidar and radiosondes were used in conjunction with the radar and radiometer measurements to classify cloud scenes as all-ice, all-liquid, mixed-phase, or precipitating so that the appropriate retrieval techniques could be applied.

Profiles of ice cloud properties, including the ice water content (IWC), ice water path (IWP), particle characteristic size (i.e., the mean diameter, D_{mean}), and particle concentration, were derived using three techniques. The radar-radiometer, tuned regression technique of Matrosov (1999) utilizes the infrared radiometer measurements of the cloud optical depth to constrain power-law relations between radar reflectivity and IWC. The Doppler velocity technique (Matrosov et al. 2002) is based on a relationship between particle size and fall speed. These two techniques use a bulk particle-size-to-density relationship that allows for the consistent retrieval of size from water content (for the first technique) and water content from size (for the second technique). A third technique utilizes empirical power-law relationships between radar reflectivity and ice cloud parameters with a monthly set of empirical coefficients derived from periods when the first two techniques were applicable. Since the first ice retrieval technique relies on infrared measurements, it is only useful for cirrus clouds that are not radiometrically obscured. Therefore, this technique was used relatively infrequently. The technique was not used at all after June 1998 because the AERI became inoperational. The second and third ice retrieval techniques, since they only rely on radar measurements, were used in all ice clouds observed by the radar. For the subset of cases for which all three ice retrievals could be performed simultaneously, particle sizes showed a 33-38% standard deviation between techniques with biases no larger than 10%. Retrieved IWCs showed standard deviations of 60 to 68% with biases less than 15%. Matrosov et al. (2002) showed agreement with in situ measurements on the order of 25% and 55% for retrieved particle size and IWC, respectively, for one case study comparison at SHEBA.

Profiles of liquid cloud properties, including liquid water content (LWC), LWP, droplet effective radius (R_e), and droplet concentration were also performed using three techniques. The Frisch et al. (1995) radar-radiometer technique combines LWP retrievals from the MWR with radar reflectivity measurements to determine microphysical profiles. Additionally, two empirical, power-law radar reflectivity techniques were employed; the first uses a fixed droplet concentration and the second allows the concentration to vary as a function of reflectivity. The radar-radiometer technique requires that all liquid in the atmospheric column be contained in all-liquid layers. Thus, when mixed-phase clouds are present this technique is not applicable. For the subset of cloud cases for which all three liquid techniques could be applied, effective radius retrievals showed a standard deviation of 25% with no significant bias. Retrieved LWCs had standard deviations of about 70% with biases between techniques of 15% or less. In statistical comparison with aircraft in situ observations made at SHEBA, retrieved droplet sizes were in good agreement, however retrieved LWCs were 20 to 40% smaller than aircraft measurements.

Preliminary (and more approximate) retrievals have been made for mixed-phase and precipitating cloud scenes. However, only the results for the all-ice and all-liquid cloud retrievals discussed above are presented in the following section.

Results

An example of retrieved cloud IWC and LWC from June 10, 1998, at SHEBA is shown in Figure 1. On this day there was a low-level liquid cloud under a high cirrus layer. For this cloud scene, all three liquid retrieval techniques could be applied to the low-level layer since no cloud liquid was contained within the upper cirrus. Only the Matrosov et al. (2002) and empirical techniques were applicable for the cirrus layer because the low-level liquid radiometrically obscured the infrared measurements.

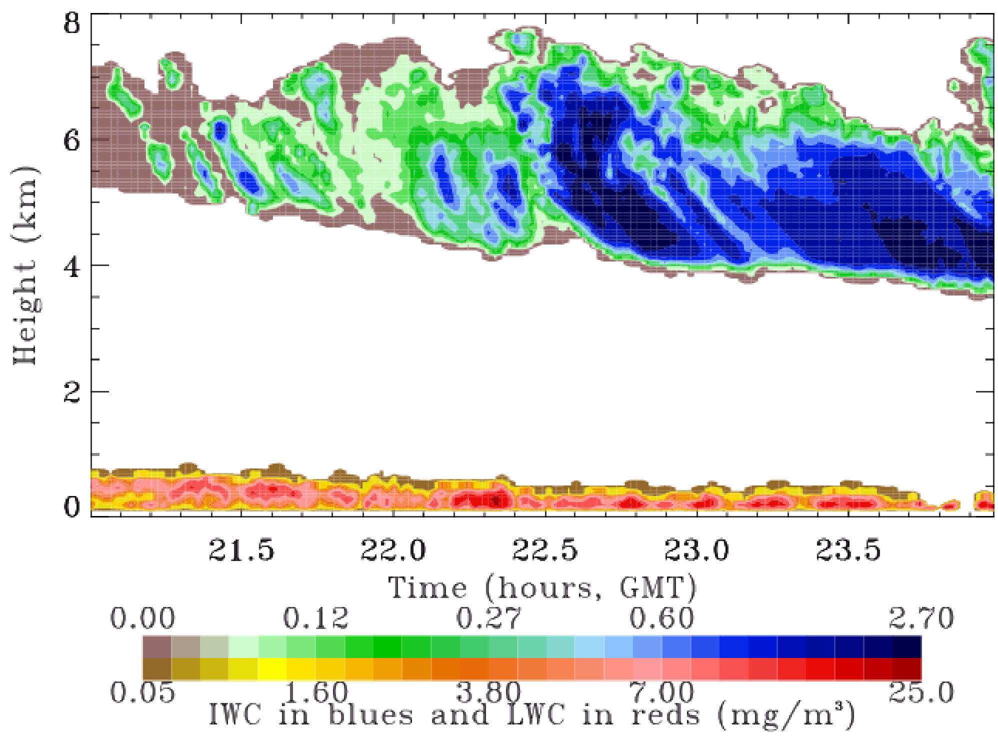

Figure 1. Time-height contours of retrieved LWC and IWC for June 10, 1998, at SHEBA.

The annual cycle of SHEBA measurements reveals substantial annual variation in the fraction of time that different cloud types were present. Figure 2 shows monthly-average cloud fractions for each of six cloud/precipitation classification categories. Frequently more than one cloud type existed simultaneously (i.e., Figure 1); therefore, the sum of the cloud type fractions may be higher than the total

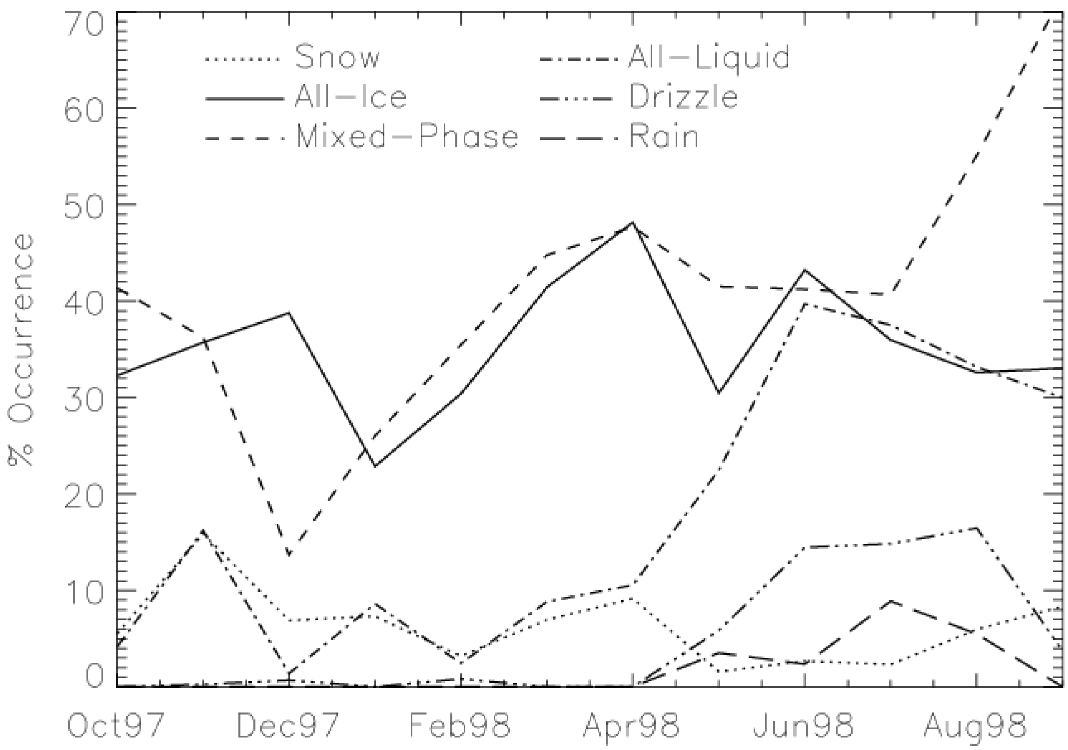

Figure 2. Monthly averages of cloud type fraction for the SHEBA annual cycle.

cloud fraction in some months. All-ice clouds are prevalent in all seasons in the Arctic, showing some monthly variability but no clear annual trend. Liquid clouds occur about 10% of the time in winter and increase to 35% of the time in summer due to warmer temperatures and higher levels of atmospheric moisture. Of particular interest is the high frequency of occurrence and annual variation of mixed-phase clouds. These data show that mixed-phase clouds occur most frequently in the transition seasons and relatively less frequently in mid-winter and mid-summer. The single-phase cloud scenes over the full annual cycle are described here using monthly and yearly averages for each retrieved parameter.

All-ice clouds were observed above the SHEBA ice camp 31% of the time. Monthly averages of ice particle sizes and water contents are shown in Figure 3 for each of the three ice cloud retrieval techniques. The Matrosov et al. (2002) and empirical techniques were run on all clouds classified as ice while the Matrosov (1999) technique could only be applied to optically thin clouds that were not radiometrically obscured. The three techniques show monthly agreement in particle size within about 30% with the smallest particles observed in the winter and the largest particles observed in the summer. IWCs follow a similar yet substantially shifted annual trend with the smallest values in spring and the largest values in fall. IWC retrievals agree to within 50%, except for during the winter when the

Matrosov (1999) results are about half as much as those from the other techniques. This wintertime difference is likely due to the limited set of ice clouds to which the Matrosov (1999) technique was applied. Annual averages and standard deviations for each retrieval technique are summarized in Table 1a.

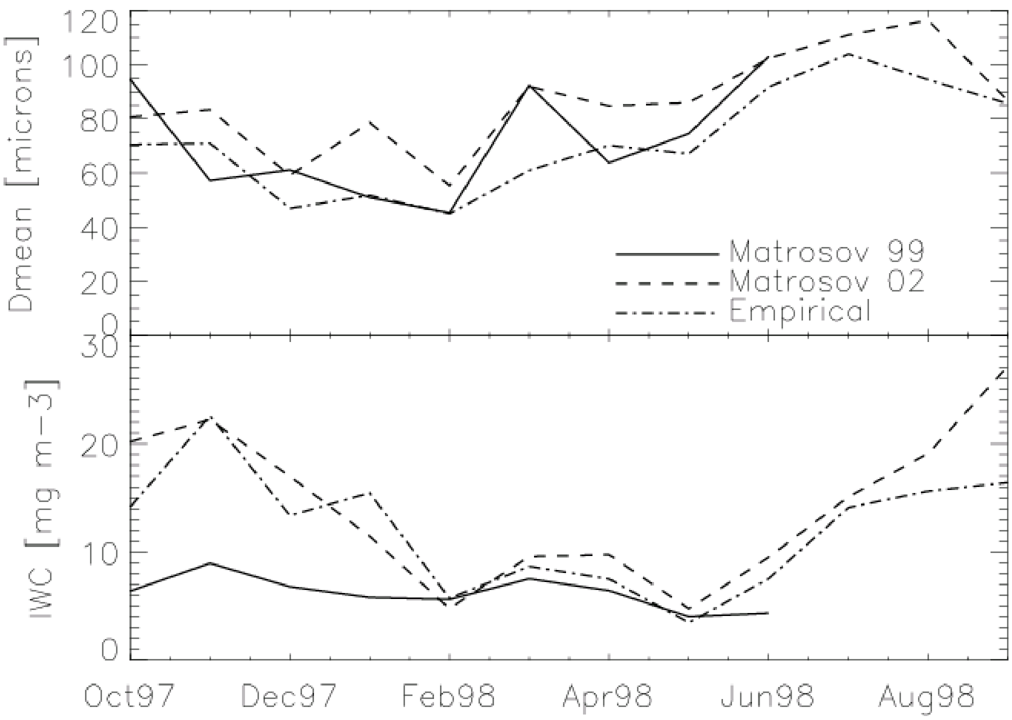

Figure 3. Monthly averaged ice particle D_{mean} and IWC using three ice cloud retrieval techniques.

Table 1. Annual mean and standard deviation of retrieved cloud parameters for each retrieval technique and annual mean values with ranges of monthly mean values for (a) ice clouds and (b) liquid clouds. M99=Matrosov (1999), M02=Matrosov et al. (2002), Emp=Empirical ice, F95=Frisch et al. (1995), Emp1=Fixed concentration empirical liquid, Emp2=Variable concentration empirical liquid.

(a)	D_{mean} [μm]		IWC [mg m^{-3}]		IWP [g m^{-2}]		(b)	Re [μm]		LWC [mg m^{-3}]		LWP [g m^{-2}]	
	Mean	***StDev***	***Mean***	***StDev***	***Mean***	***StDev***		***Mean***	***StDev***	***Mean***	***StDev***	***Mean***	***StDev***
M99	72	49	7	9	21	23	**F95**	7.1	3.6	96	110	56	48
M02	90	53	14	26	37	54	**Emp1**	6.8	2.5	80	90	38	44
Emp	73	43	12	22	33	49	**Emp2**	6.9	2.2	83	110	40	49
Annual Mean Values							**Annual Mean Values**						
	Mean	***Range***	***Mean***	***Range***	***Mean***	***Range***		***Mean***	***Range***	***Mean***	***Range***	***Mean***	***Range***
Ice	80	40-120	10	4-25	30	10-60	**Liquid**	7	5-8	85	4-130	40	15-80

All three-ice cloud techniques were highly correlated for retrieved ice cloud parameters above about 1 km. Correlation with the Matrosov et al. (2002) Doppler velocity technique degraded above 6 km due to contaminations in the Doppler velocity measurements from the horizontal winds because the radar was slightly out of vertical alignment. Vertical profiles of retrieved ice cloud parameters (not shown) indicate particle sizes and mass content growing from cloud top down to approximately 1/4th of the cloud depth from the cloud base, with rapid sublimation of cloud particles in the lowest quarter of the cloud depth.

Annual averages of ice cloud microphysical parameters (taking into consideration known sampling, instrument, and retrieval issues) indicate mean diameters of 80 μm, IWCs of 9-12 mg m^{-3}, and IWPs of 25-35 g m^{-2}. These values and the annual range of monthly averaged values are summarized in Table 1a.

All-liquid clouds were observed at SHEBA 14% of the year. Both retrieved droplet sizes and LWCs show a minimum in winter and a maximum in the summer when there is more moisture available for cloud formation (Figure 4). We note that the monthly averaged data points for October and/or November appear to be somewhat inconsistent with the other monthly values and may have been impacted by radar sensitivity issues during those months. In general, the Frisch et al. (1995) technique results are based on fewer samples than the results from the other techniques. This technique was not used at all for the months prior to May 1998 because cloud scenes for which the technique is useful did not occur in that time period. Retrieved effective radii demonstrate agreement between the three

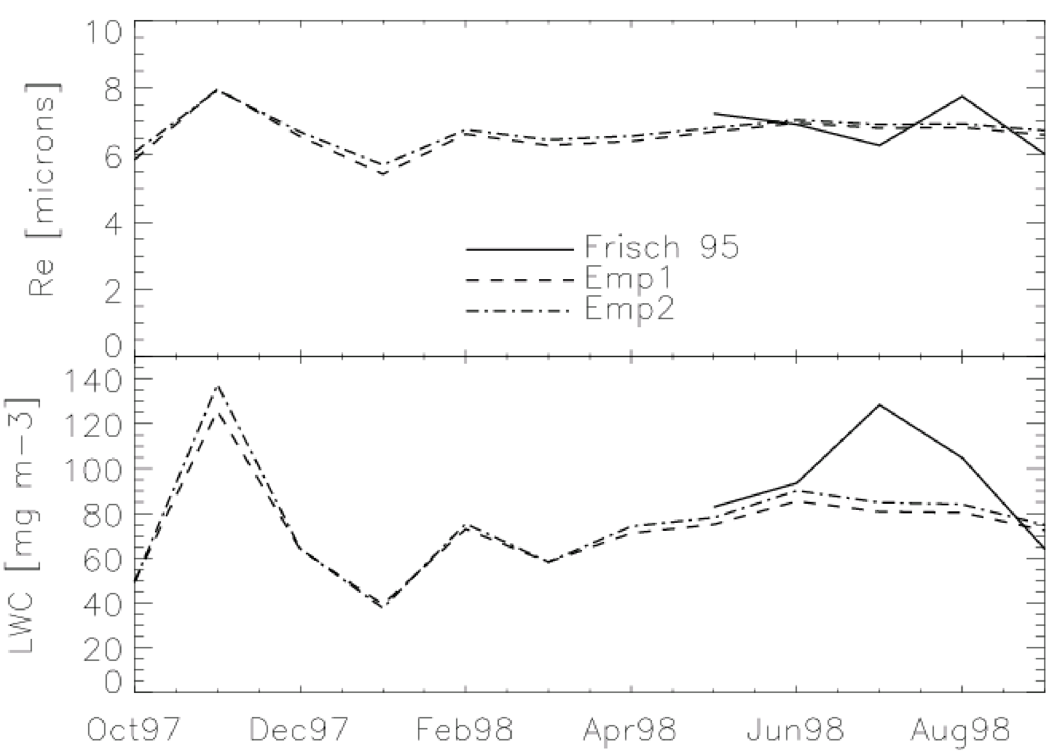

Figure 4. Monthly averaged liquid cloud R_e and LWC using the three liquid cloud retrieval techniques.

retrieval techniques of better than 10% in a monthly mean sense. LWCs agree well in most months; however, in the months of July and August the Frisch et al. (1995) results, which are based on the MWR-derived LWP, are about 50% larger than the empirically derived values of LWC. Similar discrepancies are observed in the LWP retrievals. Underestimation of LWP by the empirical techniques may be due to a priori retrieval assumptions (such as the assumed values and/or profile shapes of droplet concentration and logarithmic width of the droplet size distribution) or due to the differences in atmospheric volumes observed by the radar and MWR. Table 1b summarizes the annual averages and standard deviations of liquid cloud parameters derived from each retrieval technique.

Liquid clouds at SHEBA were semi-adiabatic with droplet sizes and water contents growing from cloud base to about 2/3 of the averaged cloud depth from the base (not shown). The top 1/3 of the average cloud depth contained highly variable profiles, demonstrating variability in cloud-top mixing and/or overall adiabatic nature.

Considering all sampling, instrumental, and retrieval issues, Arctic liquid clouds contain average effective radii of 7.0 μm, LWCs of 85 mg m^{-3}, LWPs of 30-40 g m^{-2}, and droplet concentrations of about 50 cm^{-3}. These values and the annual range of monthly averaged values are summarized in Table 1b.

Summary

This radar-based cloud dataset is unique in that it gives a first look at the variability of cloud microphysical properties and cloud type occurrence over an annual cycle in the Arctic. Furthermore, it demonstrates the ability to apply cloud retrieval techniques to diverse cloud scenes observed in all seasons of the year. Cloud retrievals have been applied to all clouds observed above SHEBA and therefore provide an excellent dataset for comparisons with satellite observations and testing of model parameterizations. This dataset is currently being used by a number of modeling groups (e.g., Morrison et al. 2002). Finally, the cloud microphysical profiles presented here are being used to calculate realistic profiles of atmospheric radiative heating rate. A similar cloud dataset from the ARM-NSA site is being refined. All SHEBA and NSA retrievals to date are displayed on the Internet at: http://www.etl.noaa.gov/arctic.

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Corresponding Author

M. D. Shupe, matthew.shupe@noaa.gov, (303) 497-6471

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