Radar-Based Retrievals of Cloud Properties in the Arctic and New Results from SHEBA

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Introduction

Clouds play a crucial role in the radiative balance of the earth's surface, particularly in the Arctic where they participate in various feedback mechanisms with the underlying surface that consists of a complex mixture of snow, sea-ice, and open water. Our current understanding of clouds, and especially their representation in climate models, is limited. Longer term observational studies of the macro- and micro-physical properties of clouds, particularly in understudied regions like the Arctic, are necessary to more clearly elucidate many cloud-related factors: average bulk cloud properties, cloud formation and persistence mechanisms, and the interactions of clouds and radiation. A clearer picture of clouds is needed if we expect to accurately predict weather or model clouds in future climates.

The Surface Heat Budget of the Arctic Ocean (SHEBA) project was created to study the ice-albedo and cloud-radiation feedback mechanisms in the Arctic. The project, conducted from a ship frozen into the permanent ice pack north of Alaska during October 1997 to October 1998, has provided data over an annual cycle with which to study these feedback mechanisms and which has greatly increased the existing observations of heat-related parameters in the Arctic. Recent work has demonstrated the significant influence clouds have on the radiation budget over the Arctic Ocean (Intrieri et al. 2001). This study focuses on measurements taken at the SHEBA ice station by a cloud radar and two different radiometers that are useful for retrieving various cloud microphysical parameters. Due to the similarity between the measurements from SHEBA and those made at the Atmospheric Radiation Measurement (ARM) Program Cloud and Radiation Testbed (CART) sites, all techniques discussed here can be applied to measurements taken at the different ARM sites. Briefly summarized here are the instruments and retrieval techniques employed in this study, the process of characterizing cloud phase using various remote and in situ measurements, and yearly retrieved microphysical statistics for all-ice and all-liquid clouds occurring at SHEBA.

Instruments and Techniques

The cloud microphysics retrievals employed here are based on radar reflectivity measurements made by the vertically-pointing, 35-GHz, Millimeter Wave Cloud Radar (MMCR) at SHEBA, which is similar to the MMCRs used at the other ARM sites. In addition to the radar, the Microwave Radiometer (MWR) and Atmospheric Emitted Radiance Interferometer (AERI), both operated by ARM at SHEBA, provide supporting radiometric information for a few of the cloud retrieval techniques.

Liquid cloud microphysical retrievals are performed using two techniques. The radar-radiometer technique (Frisch et al. 1995; 1998) requires the column integrated liquid water path (LWP) derived from MWR measurements to constrain the distribution of liquid throughout the cloud, which is done according to the reflectivity profile. This technique provides estimates of cloud liquid water content (LWC) and droplet effective radius (Re) profiles and is only useful when all of the column liquid is contained within all-liquid cloud layers that are fully observed by the radar. A second, much simpler, technique is based on empirical regressions between radar reflectivity (Z) and liquid cloud parameters. The coefficients used in the standard Z-Re and Z-LWC relationships were tuned to the Arctic region using aircraft in situ measurements of cloud droplet size distributions taken during the summer of 1998 near SHEBA (Frisch et al., manuscript in preparation, 2001).

Ice cloud microphysical retrievals of ice water content (IWC), mean particle diameter, and particle concentration were similarly performed using both simple and multi-sensor techniques. Using the infrared sky brightness temperature, obtained here from the AERI, as a proxy for optical depth, Matrosov (1999) demonstrated a method to tune simple empirical relationships between radar reflectivity and IWC to a given cloud scene. Such a tuning of the Z-IWC relationship coefficients greatly improves the retrievals over any set of a priori coefficients. Assumptions about particle density are then applied to retrieve mean particle diameters from the estimated IWC. This technique only functions when there is no liquid in the atmospheric column that would radiometrically obscure the brightness temperatures of the ice cloud. When liquid is present beneath an ice cloud, or other conditions prevent the use of the tuned regression technique, the simple Z-IWC relationship was employed. The coefficients used in this relationship were the mean values derived from the tuned regression technique; therefore, although not tuned specifically to a given cloud scene, they are indicative of clouds observed in the SHEBA region. This radar-only retrieval technique can also be used to retrieve the ice component of mixed-phase clouds since the larger ice particles will dominate the radar signal, which responds to the sixth power of particle size. All single-phase retrieval techniques and their direct application to the SHEBA data set are discussed in more detail in Shupe et al. (2001).

Cloud Classification

Clouds were classified at SHEBA using information from a combination of instruments: radar reflectivity, Doppler velocity and spectral width, MWR-derived LWP, radiosonde profiles of temperature and humidity, and lidar measurements of depolarization ratio which yields information on cloud particle phase. The first cut classification of all SHEBA cloud scenes was done subjectively (by a human) but an automated algorithm based on a fuzzy logic system of probability density functions is being developed which will provide a more consistent, if not more accurate, classification of cloud type. For the SHEBA year, all-ice clouds were observed somewhere in the atmospheric column 35% of the time and all-liquid clouds were observed 20% of the time. Of these percentages all-ice clouds were the only clouds observed in the column 14% of the time, while all-liquid clouds were the only clouds in the column 10% of the time. Thus, 76% of the time the atmospheric column above SHEBA contained a mixture of all-ice, all-liquid, mixed-phase, and/or precipitating clouds.

Cloud Microphysics Results

Some cloud retrieval technique was performed on every cloud observed by the SHEBA radar. An example of these retrievals for an 8-hour period on May 18, 1998, is shown in Figure 1. During this time period there was a low-level stratus cloud, a mid-level mixed-phase layer, and an upper ice cloud. The cloud classification data clearly demonstrate that the upper and lower layers are single-phase. The middle-layer appears to be topped by some liquid, with ice crystals falling from this layer and other

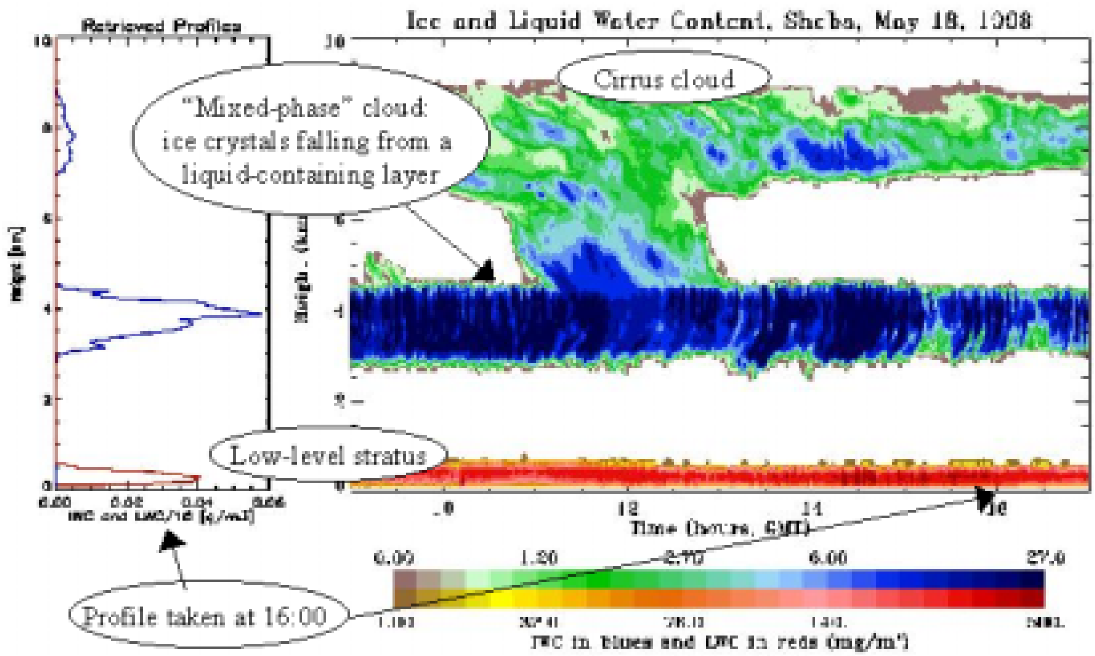

Figure 1. Time-height image of retrieved ice water content (blues) and liquid water content (reds) on May 18, 1998, at SHEBA next to a profile of the same parameters taken at 16:00. The image shows an ice cloud, a mixed-phase cloud (the ice component only), and a low-level stratus layer.

liquid containing-layers embedded in the falling ice. Since the middle layer contains some liquid, the radar-radiometer liquid cloud technique could not be used for the low-level stratus; therefore, a simple, Arctic-specific empirical relationship was used for the stratus retrievals. An empirical relationship was also used for the high ice layer since the low-level stratus radiometrically obscured the ice cloud from the surface. This ice retrieval was also performed throughout the mid-level mixed-phase layer, providing information about the ice component of this layer but not about the liquid component. For this case the ice water contents in the mixed-phase layer are much larger than those in the all-ice layer above (see profile), presumably because of differing ice crystal formation mechanisms in these two layers.

Statistics have been compiled for each microphysical parameter calculated using each applicable retrieval technique for the entire SHEBA annual cycle. Preliminary examination of monthly mean values does not demonstrate any clear seasonal variation of microphysical parameters, other than a slight increase in mean IWC during the summer. Further detailed examination, however, is necessary to confirm the absence or presence of such seasonal variability. Mean yearly statistics for the size and water content parameters are shown in Table 1. Means for each parameter calculated using two different techniques are presented. There is considerable difference between the tuned regression ice retrieval and the untuned regression. These differences are likely due to the designation of the coefficients used in the Z-IWC relationship, which were based on data from the summer months and will be reconsidered in reprocessing. The liquid cloud parameters calculated both with the radar-radiometer and the empirical regression techniques are in generally better agreement. A similar yet more rigorous analysis focused on the April through July months of SHEBA is summarized in Shupe et al. (2001), demonstrating very similar mean microphysical values.

Table 1. SHEBA yearly mean, minimum, and maximum retrieved microphysical parameters for all-ice and all-liquid clouds.

	Mean Diameter, Ice (μm)		**Ice Water Content (g/m^3)**		**Effective Radius, Liquid (μm)**		**Liquid Water Content (g/m^3)**	
	M99[(a)]	**Emp[(b)]**	**M99**	**Emp**	**F95[(c)]**	**Emp**	**F95**	**Emp**
Mean	68	55	0.006	0.019	6.9	6.5	0.08	0.14
Min	2	5	~0	~0	1	1	~0	0.001
Max	600	350	0.18	1.3	50	25	1	4

(a) M99 = the Matrosov (1999) ice cloud retrieval.
(b) Emp = empirical relationship-type retrievals. Ice statistics are for all-ice clouds only, not for the ice component of mixed-phase clouds.
(c) F95 = Frisch et al. (1995) liquid cloud retrieval.

This year-long data set of retrieved microphysical parameters will be the basis for further investigation into Arctic cloud microphysics. Current work is aimed at examining the vertical distribution of microphysical parameters both with height in clouds and with height in the atmosphere, the temperature dependence of cloud microphysics, and the seasonal variation of cloud parameters. Furthermore, study will expand to cover retrieval statistics on mixed-phase and precipitating clouds. Finally, the radiative significance of the various microphysical parameters will be examined.

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