A Comparison of Cloud Properties at Barrow and SHEBA During the Summer of 1998[(a)]

J. C. Barnard, J. C. Doran, S. Zhong, and C. N. Long
Pacific Northwest National Laboratory
Richland, Washington

Introduction

As noted by Curry et al. (1996), the retrieval of polar cloud properties from satellites is fraught with difficulty. These difficulties mandate the use of ground-based and/or aircraft measurements to determine the properties of Arctic clouds. Because of the inhospitable environment of the Arctic, such measurements have been limited, leading to a relative lack of understanding of these clouds. However, recent field campaigns are adding to the database from which a clearer picture of Arctic clouds may be established.

Data obtained from the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign during the summer (June through September) of 1998, as well as data collected from the Atmospheric Radiation Measurement (ARM) Program Barrow site during this same time period provide an unparalleled opportunity to study Arctic clouds at two widely spaced locations with far different surface properties in the summer—ice at SHEBA, and a combination of bare earth and open sea at Barrow.

The SHEBA experiment (see http://sheba.apl.washington.edu) was located atop pack ice far from any land surface. Although the SHEBA "ice camp" moved considerably during the year because of movements of the underlying ice, the approximate coordinates of the site during the summer of 1998 were about 78°N latitude and 160°W longitude. The ARM Barrow site is situated much farther south, at about a latitude and longitude of 71°N and 157°W, respectively.

Instrumentation at both sites included a Microwave Radiometer (MWR), Liljegren (1994 and 2000) and a Multi-Filter Rotating Shadowband Radiometer (MFRSR), Harrison et al. (1996). The MWR measures, among other things, liquid water path (LWP), while the MFRSR measures direct normal, diffuse, and total irradiances at six distinct wavelengths. A silicon photodiode also provides an estimate of these quantities over the shortwave (SW) broadband spectrum. For the calculations presented here, only the 415 nm MFRSR irradiances at were used. When combined with LWP, these irradiance measurements can be used to find cloud optical depth, τ_c, and cloud droplet effective radius (r_e), using the algorithm of Min and Harrison (1996). In the absence of LWP observations, the irradiances alone provide sufficient information to find τ_c but the effective radius cannot be determined.

(a) This paper is nearly identical to the paper presented at the 6th AMS Conference on Polar Meteorology and Oceanography, May 14-18, 2001, San Diego, California.

Additionally, τ_c can be derived, independently of the MFRSR, from diffuse broadband SW pyranometers, in the spirit of the algorithm developed by Leontyeva and Stamnes (1994). The backbone of these broadband calculations is the SBDART model (Ricchiazzi et al. 1998); this model is coupled with an optimization scheme that varies the cloud optical depth and effective radius until the difference between the calculated and measured broadband irradiances is minimized. Cloud optical depths calculated in this manner serve as a check on the cloud optical depths obtained from the MFRSR.

Finally, the specification of cloud properties is not complete without an estimate of the fractional cloudiness. Data from the MFRSR broadband channels can be fed to an algorithm developed by Long et al. (1999) to determine this quantity.

Data Quality Issues

The first, and critical, step in the calculation of cloud properties was an assessment of data quality from the instruments mentioned above. Data from the Barrow MFRSR appears to be of very good quality and did not require a lot of attention. In contrast, the MFRSR at the SHEBA ice camp suffered from numerous problems, including shading errors and noise of unknown origin. These ills have been detailed in the presentation of Barnard et al. (2000). Since the time of this presentation, a major calibration problem associated with the SHEBA instrument has been discovered and corrected by recalibrating the MFRSR sensing head by comparing the output of the head to a calibration standard.

Data from the MWRs, at both Barrow and SHEBA, are presently mired in controversy. A comparison between aircraft measurements of LWP (Curry et al. 2000), taken roughly above the SHEBA ice camp, with the LWP derived from the MWR, suggests that the SHEBA MWR reads high by a factor of about two. The possibility that the MWR readings may be too high has been reinforced by Lin et al. (2001). They developed an alternative LWP retrieval scheme based on spectroscopy that is thought to be more appropriate for clouds with significant super-cooled water (such clouds might be expected to occur in polar regions). Using this new retrieval reduces the LWP by about 47% over the values based on the ARM standard retrieval.

The controversy regarding the MWR LWP has yet to be resolved. Fortunately, even if the current LWPs obtained from the ARM archive are too high, these LWPs will not greatly affect the calculations of cloud optical depth. This is not case for droplet effective radius, however, for r_e is highly sensitive to values of LWP. In approximate terms, we have

$$R_e \approx \frac{3}{2}\frac{\text{LWP}}{\tau_c} \tag{1}$$

(Stephens 1978) and the effective radius is approximately proportional to the LWP because τ_c is not very sensitive to r_e over a wide range of plausible droplet effective radii. Thus, if the LWP path is too large, the effective radius will be too large also, and the amount that r_e exceeds its "true" value is proportional to the error in LWP measurements; for example, if the LWP is too large by a factor of two, r_e will likewise be too large by a similar amount. Because of the uncertainty associated with the LWP, and therefore r_e, we will only present the results of our optical depth calculations.

The calculated results for τ_c depend critically on surface albedo, particularly for the large albedos typical of ice and snow surfaces. Spectral albedos were obtained from the Web site (http://www.joss.ucar.edu/data/perovich/ICEWEB/spectalb.htm). These data are also available on CD-ROM (Perovich et al. 1999).

Results

Once the data quality issues were resolved, we can calculate the cloud properties of interest. For these calculations we used the algorithm developed by Min and Harrison (1996). In brief (and oversimplified) terms this algorithm uses diffuse transmission at 415 nm to infer cloud optical depth: the less the transmission the greater the cloud optical depth. A typical time series, for 5-minute averages of cloud optical depths, for the SHEBA ice camp on March 15, 1998, is shown in Figure 1.

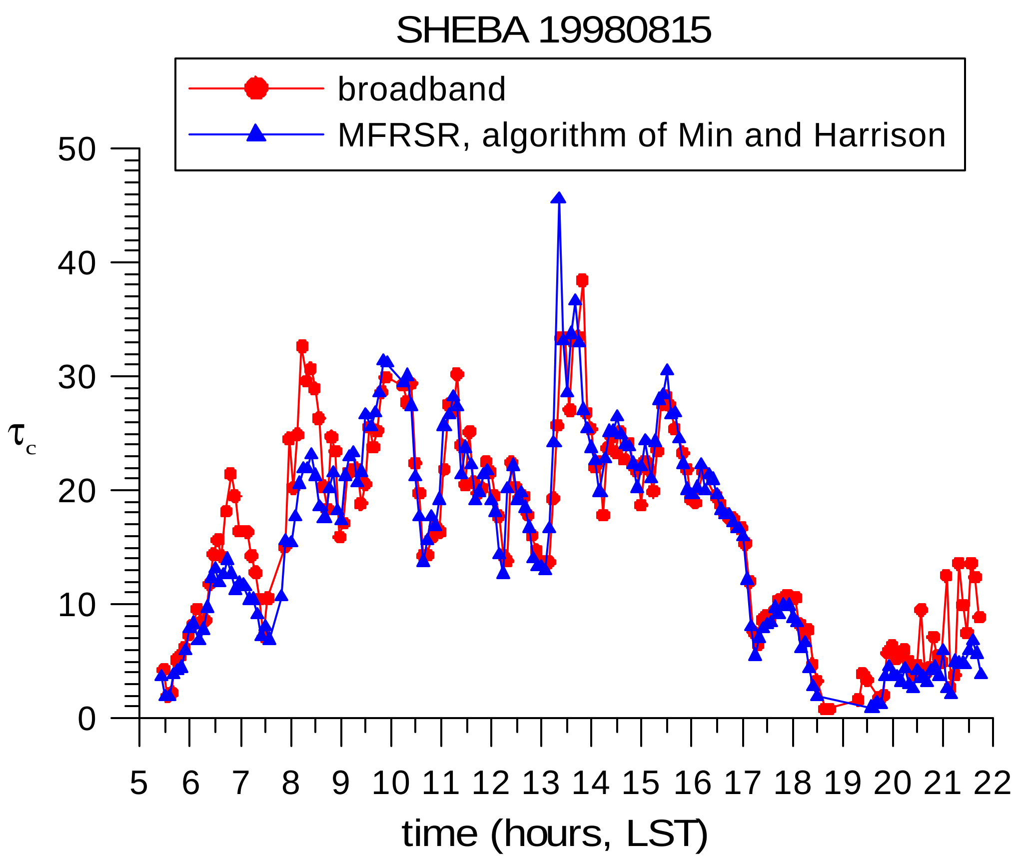

Figure 1. Cloud optical depth, τ_c, plotted versus time. The circles are optical depths derived from the broadband radiometers while the triangles are the same derived from the MFRSR.

In this figure, τ_c is shown as calculated by the Min and Harrison algorithm—the triangles—and as calculated from diffuse broadband irradiances—the solid circles. The agreement between the two methods is generally very good, although τ_c derived from the MFRSR is sometimes less than τ_c obtained from the broadband radiometers. Such good agreement was found on many, but not all days for which we performed broadband calculations,[a] and when there was some disagreement, the tendency of the MFRSR-derived optical depths to be lower was evident. To illustrate this difference, Figure 2 shows a scatterplot of cloud optical depths derived from the MFRSR data versus optical depth from the diffuse broadband radiometer.

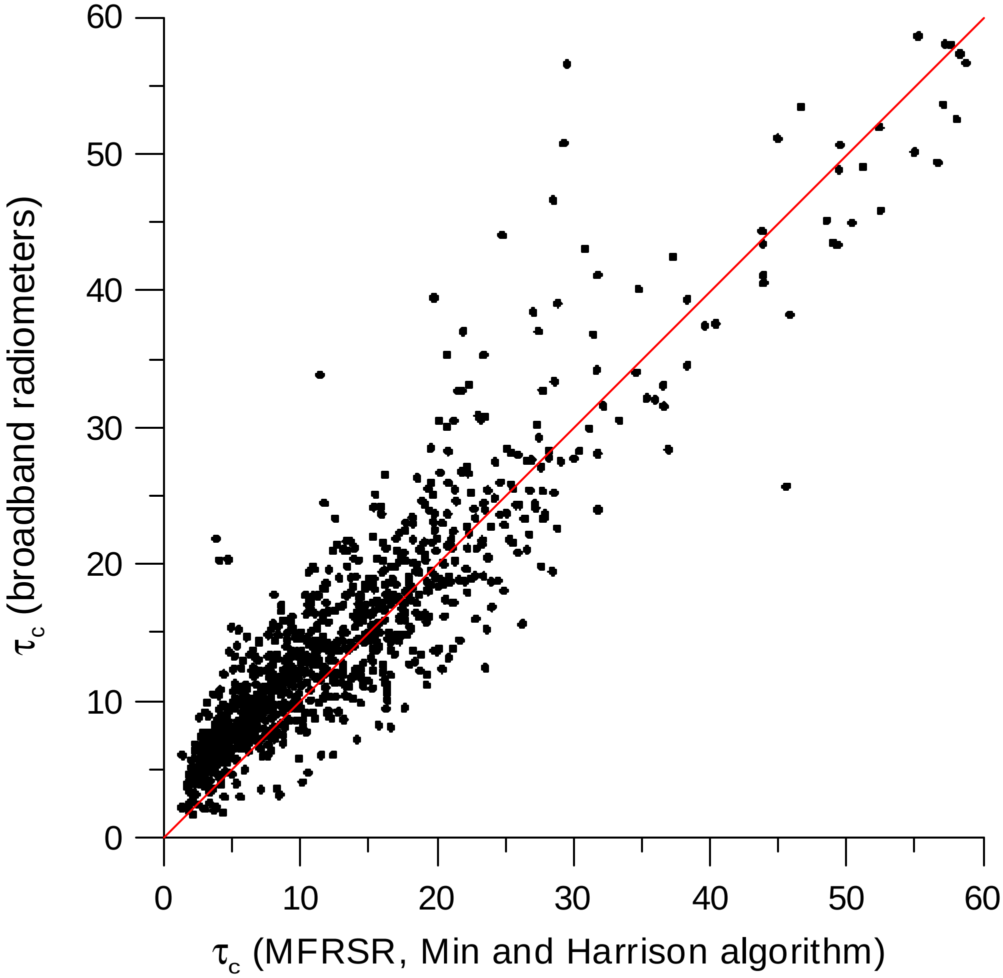

Figure 2. Cloud optical depth from the MFRSR versus cloud optical depth from the diffuse broadband radiometer. In the figure the number of points has been decimated by a factor of three for clarity. The diagonal line has a slope of one.

(a) The broadband calculations are time-consuming and we have not run them for every single day of the summer of 1998; instead we ran the broadband code for about 45 days that were evenly distributed over the summer months.

Figure 2 reveals that τ_c from the broadband radiometers tends to read about 2 optical depth units larger than the τ_c obtained from the MFRSR data; this conclusion may be confirmed by examining the means and medians, which indeed do differ by about 2 units. The agreement is encouraging, given the problems with the SHEBA MFRSR. A similar process, comparing MFRSR-derived optical depths to those from the broadband radiometers was also undertaken for the Barrow site and no significant difference between the optical depths was found for the cases that we have examined. Mindful of these comparisons, we conclude that our optical depth calculations are reasonably good at both sites.

Table 1 shows the median cloud optical depths, as well as the 25th and 75th percentile values, calculated using the MFRSR data for the summer of 1998, both at SHEBA and Barrow. We have also included the cloud properties for Barrow during the summer of 1999. Although we have only completed about half the broadband calculations for the summer months at the SHEBA site, it is probable that, from these existing runs, we have sufficient statistics to estimate τ_c. This estimate is also shown in Table 1.

Table 1. Median, 25th and 75th percentile values of cloud optical depth, τ_c, for the SHEBA and Barrow sites for the years indicated.

Site	25th percentile	t_c (median)	75th percentile
SHEBA - 1998	4.3	8.4	14.9
SHEBA – 1998 (broadband)	6.3 (estimated)	10.4 (estimated)	16.9 (estimated)
Barrow - 1998	9.2	14.3	22.8
Barrow - 1999	6.9	10.4	15.9

Again, the small differences between the broadband estimates and the MFRSR-derived values suggests that the optical depths calculated for the SHEBA site are reasonably accurate to about 2 units of optical depth.

That the SW optical depth at the two sites is relatively small is consistent with other measurements of the optical depth of arctic stratus clouds. For example, Leontyeva and Stamnes (1994) used broadband pyranometers to infer cloud optical depth at Barrow, Alaska and their results indicate an average optical depth over the summer months (excluding September) of about 15. Our measurements show a median optical depth of 10 and 14 for the two seasons at Barrow (including September)—a range of optical depths that is reasonably consistent with the findings of Leontyeva and Stamnes.

The results shown in Table 1 suggest a difference between cloud properties at Barrow and at the position of the SHEBA ice camp, at least during the summer months of 1998. Whether this difference would be seen in other years cannot be determined with this dataset.

We have calculated effective radii values of about 15 microns for both the SHEBA and Barrow sites. These values appear inconsistent with other measurements of this quantity. For example, using aircraft measurements over the polar ice Herman and Curry (1984) have reported a median effective radius of 7.3 microns. Thus, the effective radii reported here appear to be too high by a factor of two. This apparent overprediction of r_e may result from LWPs, which are too high (see Eq. [1]). This finding bolsters the contention that the LWPs from the ARM MWRs located in the Arctic are too large. We are now in the process of applying a more appropriate retrieval algorithm to the raw MWR data that will likely reduce the LWP values and, therefore, the effective radii.

Finally, we examine fractional cloudiness at the two sites; the daily average of this quantity is plotted in Figure 3 for the two sites. The upper and lower panels show the fractional cloudiness at the Barrow and SHEBA sites, respectively, for the months of June through September. It is clear that over this time period, the SHEBA site seems much cloudier, particularly from about the middle of summer onward, during which the fractional cloudiness is almost 1 on every day.

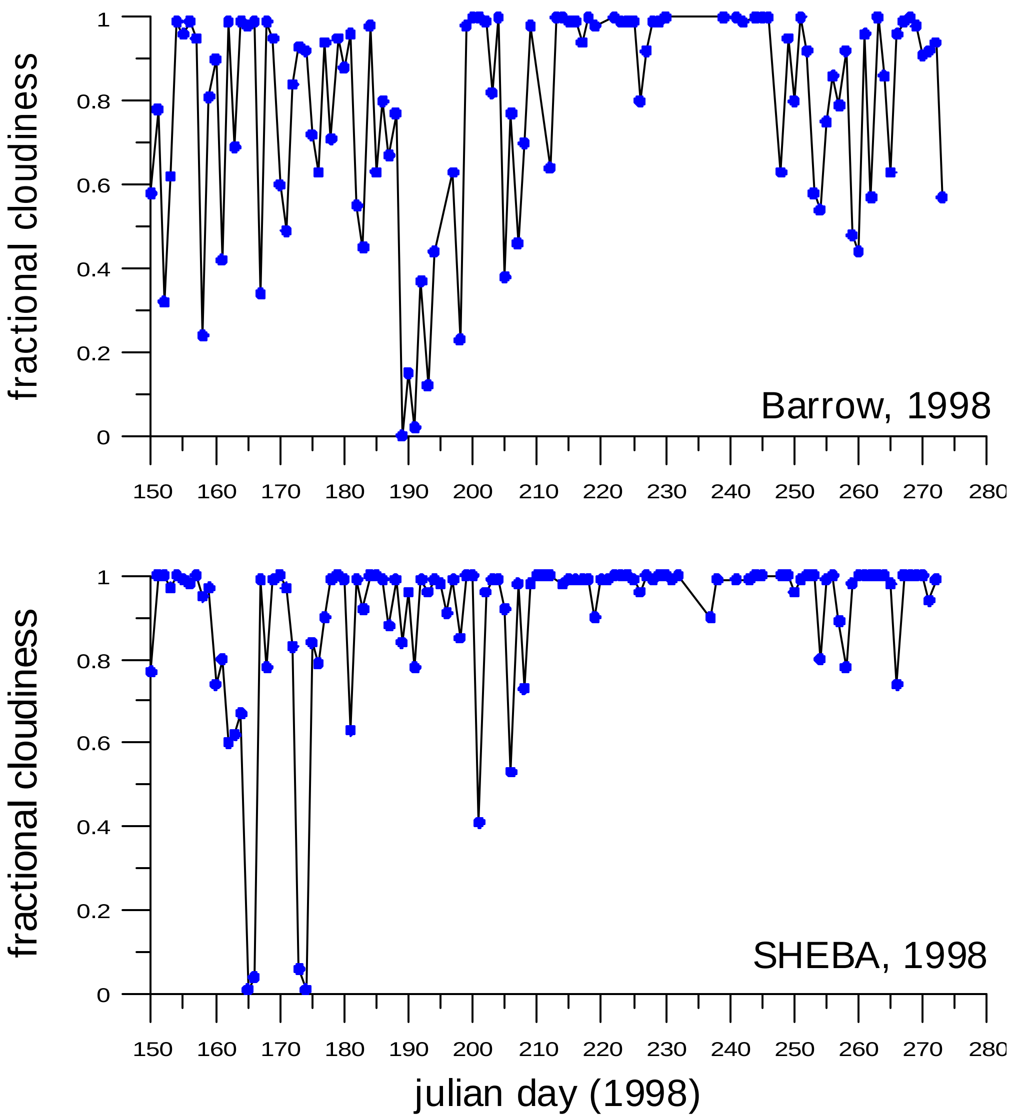

Figure 3. Fractional cloudiness, ranging from 0 (no clouds) to 1 (sky completely covered by clouds) for the SHEBA and Barrow sites. The time period shown extends from about June 1, 1998 to September 30, 1998.

Both sites, however, exhibit considerable cloudiness over the summer months. A rough measure of the cloudiness is simply the average of the fractional cloudiness over the summer, and this average is 0.78 and 0.84 for the Barrow and SHEBA sites, respectively. The Arctic skies are indeed cloudy skies!

Conclusions

Measurements taken from MFRSRs and MWRs at the SHEBA ice camp and the ARM Barrow site have been used to derive cloud optical depth and fractional cloudiness for the summer of 1998. The results indicate that, during this time period, the optical depths of the clouds over the SHEBA site are smaller than the depths at the Barrow site. The effective radii we have calculated appear to be far too high, suggesting that the LWPs from the MWRs are similarly too high. Refinement of the effective radius values awaits the resolution of the uncertainties associated with the MWR.

By examining a time series of the daily averaged fractional cloudiness at the two sites, we conclude that the SHEBA site is cloudier than the Barrow site, particularly in the last half of the summer. Although the SHEBA site is cloudier, we reiterate that the clouds at this site were "optically thinner" than the clouds over the Barrow site in the summer of 1998.

Acknowledgement

This research was sponsored by the U. S. Department of Energy under Contract DE-AC06-76RL01830 at Pacific Northwest National Laboratory. Pacific Northwest National Laboratory is operated for the U. S. Department of Energy by Battelle Memorial Institute. The ARM Program is sponsored by the U. S. Department of Energy.

Corresponding Author

J. C. Barnard, james.barnard@pnl.gov, (509) 372-6145

References

Barnard, J. C., J. C. Liljegren, Q. Min, and J.C. Doran, 2001: The use of rotating shadowband radiometers and microwave radiometers to obtain cloud properties in Arctic environments. In *11th Symposium of Meteorological Observation and Instrumentation*, January 14-18, 2001, Albuquerque, New Mexico. American Meteorological Society, Boston, Massachusetts.

Curry, J. A., W. B. Rossow, D. Randall, and J. L. Schramm, 1996: Overview of Arctic cloud and radiation characteristics. *J. Climate*, **9**, 1731-1764.

Curry, J. A., et al., 2000: FIRE Arctic clouds experiment. *Bull. Am. Met. Soc.*, **81**, 5-30.

Harrison, L., J. Michalsky, and J. Berndt, 1994: Automated multifilter rotating shadowband radiometer: An instrument for optical depth and radiation measurements. *Appl. Opt*., **33**, 5118-5125.

Herman, G. F., and J. A. Curry, 1984: Observational and theoretical studies of solar radiation in Arctic stratus clouds. *J. Climate Appl. Meteor*., **23**, 5-24.

Leontyeva, E. and K. Stamnes, 1994: Estimations of cloud optical thickness from ground-based measurements of incoming solar radiation in the Arctic. *J. Climate*, **7**, 566-578.

Liljegren, J. C., 1994: Two-channel microwave radiometer for observations of total column precipitable water vapor and cloud liquid water path. In *Fifth Symposium on Global Change Studies*, January 23-28, Nashville, Tennessee.

Liljegren, J. C., 2000: Automatic self-calibration of ARM microwave radiometer, *in Microwave Radiometry and Remote Sensing of the Environment*, ed. P. Pampaloni, VSP Press.

Lin, B., P. Minnis, A. Fan, and D. Young, 2001: Estimation of column water amounts over Arctic regions using ground-based thermal microwave and infrared measurements. In *11th Symposium of Meteorological Observation and Instrumentation*, January 14-18, 2001, Albuquerque, New Mexico. American Meteorological Society, Boston, Massachusetts.

Long, C. N., T. P. Ackerman, J. J. DeLuisi, and J. Augustine, 1999: Estimation of fractional sky cover from broadband SW radiometer measurements. In *Proc. 10th Conf. on Atmos. Rad*., June 28-July 2, 1999, Madison, Wisconsin.

Min, Q. and L. Harrison, 1996: Cloud properties derived from surface MFRSR measurements and comparison with GOES results at the ARM SGP site. *Geophys. Res. Lett*., **23**, 1641-1644.

Perovich, D. K., T. C. Grenfell, B. Light, J. A. Richter-Menge, M. Sturm, W. B. Tucker III, H. Eicken, G. A. Maykut, and B. Elder, *SHEBA: Snow and Ice Studies CD-ROM*, October, 1999.

Ricchiazzi, P., S. Yang, C. Gautier, and D. Sowle, 1998: SBDART: A research and teaching tool for plane-parallel radiative transfer in the earth's atmosphere. *Bulletin of the American Meteorological Society*, **79**, 2101-2114.

Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization schemes. *J. Atmos. Sci*., **35**, 2123-2132.