Project Report
Validation of CERES Cloud Retrievals Over the Arctic with Surface-Based Millimeter-Wave Radar

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Activities over the April, 1999 to May 2000 reporting period have fallen into 6 major areas:
1) In-situ validations of remote radar-radiometer retrievals with aircraft measurements
2) Resolution of discrepancies in the retrievals of liquid water path from microwave radiometers
3) Adaptation of ice and liquid retrievals to Arctic cloud conditions
4) Comparison of SHEBA arctic cloud properties to satellite measurements
5) Ingest of the data from the DOE/ARM site in Barrow, Alaska
6) Statistical characterization of arctic clouds

Each of these areas is summarized in the following annual progress report. Note that while the following discussion only explicitly refers to retrievals of Liquid Water Content (LWC) and Ice Water Content (IWC), retrievals of hydrometer sizes and concentrations are also implied. The "radar-radiometer" technique for LWC retrievals utilizes a microwave radiometer which measures brightness temperatures at 23.8 and 31.4 GHz, the "radar-radiometer technique for IWC retrievals utilizes the 10.95 - 11.3 micron bands from a spectral infrared radiometer.

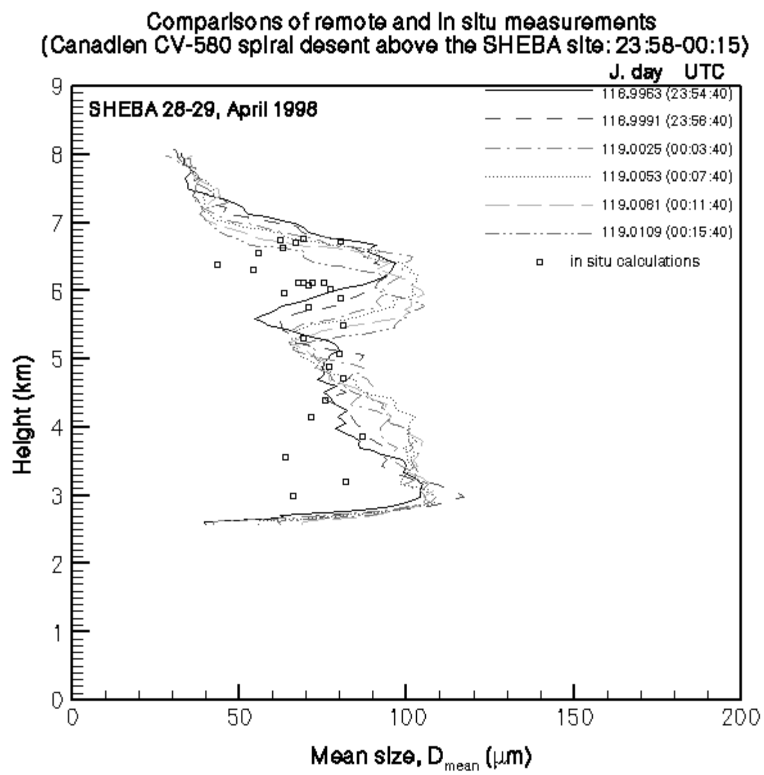

Figure 1

1) In-situ validations of remote radar-radiometer retrievals with aircraft measurements

After the aircraft data and the preliminary radar-retrievals of cloud properties from the SHEBA program became available over the last year, there was a initial flurry of interest in doing comparisons in Arctic clouds from a large number of research groups. At present however, the three main groups that seem to be actively pursuing this activity (in collaboration) are NOAA/ETL (Matrosov, Shupe, Uttal), University of Washington (Hobbs) and the Canadian Environmental Services (Isaac and Korolev). Figure 1 shows an example of retrievals of IWC from the radar-radiometer method and data collected by the Canadian Convair on May 28th. For this single layer, all-ice cloud, with no complicating low level liquid layers, the ice retrieval technique appears to be working extremely well.In contrast, Figure 2 shows some comparisons of examples of retrieved LWC from the radar-radiometer method and data collected by the

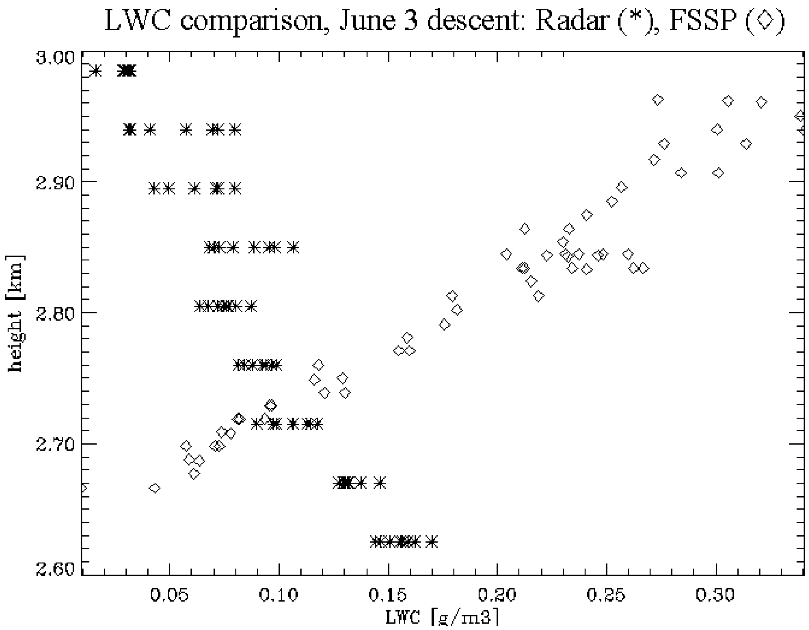

Figure 2

University of Washington Convair on June 3 for a cloud that was known to have ice particles mixed in a liquid layer. In this case, the "contamination" of the liquid layer with a few scattered ice crystals had a large effect on the radar reflectivities and the retrieved LWC decreased as a function of cloud height which is directly opposite to the increasing profiles of LWC as detected by the aircraft measurements. This serves to illustrate the retrieval techniques must be applied judiciously, and only to appropriate case to prevent serious miscalculations. Other comparisons between the surface retrievals and the aircraft measurements of LWC in liquid cloud cases that were not contaminated by ice crystals showed significantly better agreement.

2) Resolution of discrepancies in retrievals of liquid water path from microwave radiometer

The radar-radiometer technique for estimating LWC content can of course be no more accurate than the retrieval of LWP from the microwave radiometer brightness temperatures. The University of Colorado did a number of comparisons between aircraft measurements of LWP and the LWP measurements made by the DOE/ARM microwave radiometer at the SHEBA ice camp. Although these comparisons are potentially problematic for a number of reasons (mismatches between the extent of cloud sampled by the aircraft and the atmospheric column sensed by the radiometer, disagreements between the various LWC sensors on the aircraft, low LWP amounts in Arctic clouds etc), the aircraft measurements consistently indicated that the radiometer measurements were too high by a factor of about 1.6. Since NOAA/ETL originally developed and supplied the algorithms to DOE/ARM for the radiometer retrievals, it was efficient to have NOAA/ETL investigate the discrepancies in detail. It has been determined that the difference lies in the wavelength and temperature dependant absorption coefficients for both the dry atmosphere and for liquid clouds. The absorption coefficients that were being used were based on models that had been developed for and tested for warm stratus clouds. In the arctic atmosphere, there are two significant differences; first the atmosphere is much drier, and secondly, clouds are more likely to have supercooled liquid water. This is important since the absorption coefficients vary as a function of the dielectric content of supercooled liquid water which is not a well measured physical constant. Testing of three molecular absorption models indicated that differences were large enough to account for the discrepancies indicated by the aircraft measurements. At the time of this report, we have reprocessed the SHEBA data sets which brings the radiometer and aircraft measurements into better agreement. It will be necessary to perform similar reprocessing on the DOE/ARM North Slope of Alaska radiometer data sets to acquire best possible validation data sets of LWP and LWC for MODIS and CERES. It should be noted that this investigation indicates that the DOE/ARM program has done an excellent job with microwave radiometer calibrations and do not constitute a criticism of the DOE/ARM program, but rather unexpected issues related to supercooled liquid water which are more prevalent in arctic clouds than in lower latitude clouds.

3) Adaptation of ice and liquid retrievals to arctic cloud conditions

In the retrieval of LWC, we are presently utilizing a technique which depends on a relationship between radar reflectivity and LWC which is determined completely from data measured by FSSP probes on aircraft (where both radar reflectivities and LWC are calculated from the FSSP measurements of particle concentrations and size spectra). The regression coefficients for this method was developed originally using data from FSSP data that was collected during an IOP at the Southern Great Plains ARM site. Recalculation of the relationship using aircraft data from the FIRE-Arctic Clouds Experiment resulted in a significantly different coefficients in the regression relationship, primarily resulting from significantly different droplet concentrations between the clouds observed in Oklahoma (400 cc^{-1}) and the SHEBA ice camp (150 cc^{-1}). This new arctic relationship will be applied to the North Slope of Alaska data for comparison with the EOS cloud data sets.

In the retrieval of IWC, there are a number of related radar-radiometer techniques which can be used. It is often the case that the technique of choice (utilizing all possible radar and radiometric information) can not be applied in the arctic for two reasons. First, the determination of optical depth which is one of the intermediary steps in this process can be problematic because of the extremely low optical depths which often occur in all-ice arctic clouds, and secondly, low level liquid layers often obscure upper level ice clouds making application of the radar-radiometer techniques impossible. To address this issue, we have been experimenting with the use of empirical relationships between IWC and reflectivity. Such relationships have been in use for many years, however, the results can vary, depending on which relationship is chosen, by an order of magnitude. To make the technique more applicable to arctic clouds, we are taking periods during which we can do highly reliable retrievals (single-layer, not too optically thin, and all ice) and determining coefficients for the empirical relationship between IWC and reflectivity that can be applied to the more difficult and complex cases. The tuned coefficients for the empirical relationship are proving to be quite stable, and we are in the process of investigating seasonal and altitude related dependancies.

4) Comparison of SHEBA arctic cloud properties to satellite measurements
The satellite community has been extremely active in utilizing the radar and lidar data sets that were developed during SHEBA and placed on the archives maintained by UCAR. Comparisons have been made for cloud properties such as cloud fraction, particle sizes, optical depths and cloud top temperatures by groups at University of Washington (TOVS - Schweiger and Francis), and University of Wisconsin and University of Colorado (CASPR - Key and Maslanik), and active collaborations are presently in progress between NOAA/ETL and NASA Langley (AVHRR - Minnis) as well as NASA/GISS (ISCCP - Rossow). Preliminary comparisons

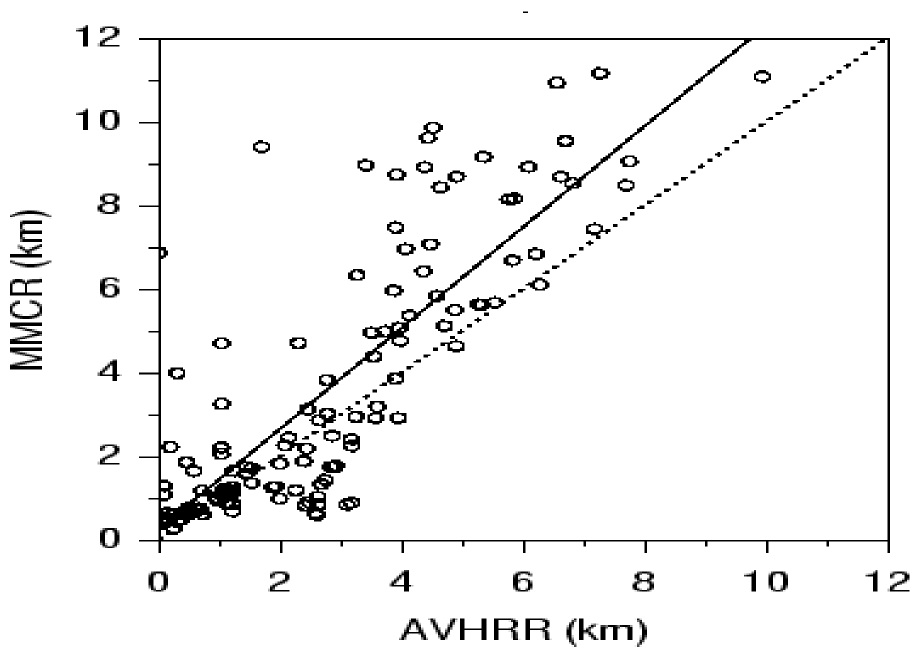

Figure 3

indicate that cloud amounts can be derived successfully by satellite, however it is essential to determine detailed, multi-spectral thresholds subjectively (Minnis et al., 2000). One of the simplest and most useful products that the NOAA/ETL research group has produced for the satellite community has been a year long file of cloud bases and tops that is a combined product that uses both the radar and the lidar data sets. This data set takes advantage of the strengths of both instruments, and accounts for the weaknesses of both instruments. Specifically, lidar bases are utilized during episodes of precipitation (since radar does not distinguish between clouds and precipitation), it utilizes radar cloud tops and multiple layer information (when the lidar is clearly attenuated), and utilizes lidar cloud boundary information for high altitude clouds with particles too small to be detected by the radar (about 15% of the time). Figure 3 shows comparison of cloud top heights from the SHEBA cloud radar and AVHRR retrievals during the FIRE-ACE experiment (April-July, 1998). The level of activity and attention that the satellite community has devoted to the SHEBA data sets would indicate that additional comparisons will commence between the surface-based cloud data sets from North Slope of Alaska and the TERRA cloud data sets as soon as both data streams are flowing smoothly.

5) Ingest of the data from the DOE/ARM site in Barrow, Alaska

A number of unanticipated problems with the data flow from the DOE/North Slope of Alaska site have significantly delayed the real-time processing of cloud retrievals. DOE is presently using a data processing procedures which creates additional products by combining information from a number of sensors, including the radar, the micropulse lidar, and radiometers. At present, this value added processing is the source for the radar data streams which are ingested into the ARM archives, but if any single instrument is missing the processing does not occur. Also, the North Slope of Alaska tends to be the last priority site for DOE when making decisions on resource allocations for processing. Therefore, missing micropulse lidar data, and conflicting priorities with the Southern Great Plains and Tropical Western Pacific sites has resulted in the unfortunate fact that there is no radar data in the ARM archives for the North Slope of Alaska, even though that radar has been on line for over two years. We are developing the following strategies to access the necessary data streams.

1) Since NOAA/ETL designed the radar for the ARM program, unprocessed radar data sets are downloaded on a daily basis at ETL for quality checking and control. It is our intention to take advantage of this “backdoor access” to the data for the real-time retrievals for EOS.

2) The original MERGE software to process DOE/ARM radar data was written by Eugene Clothiaux at Pennsylvania State University. We have contracted with Eugene to modify the MERGE software to operate on the North Slope of Alaska radar data without running the additional portions which are dependant on other data sets, for instance the micropulse lidar. At the time of this report, the software is running on some data sets, and still having problems with other data sets which need to be resolved. The MERGE software is an extremely complex program which blends information from four distinct operating modes that are employed by the radar to produce a single cloud product.

3) We have arranged with DOE/ARM to process already existing radar data sets from 1998, 1999 and 2000 and will be providing the processed data to the DOE/ARM archive. Although the TERRA satellite was not yet launched during much of this time period, the retrievals performed on these data sets will provide useful statistics for longer term comparisons to TERRA.

4) While we are working out all the data stream problems, we have used the SHEBA data sets as a prototype to develop a GUI system which allows a user to display all available data sets for a given day (radar, radiometers, rawinsondes, lidars), make decisions about which retrievals will be run for which parts of the cloud system (bracketed by time and altitude), display resulting

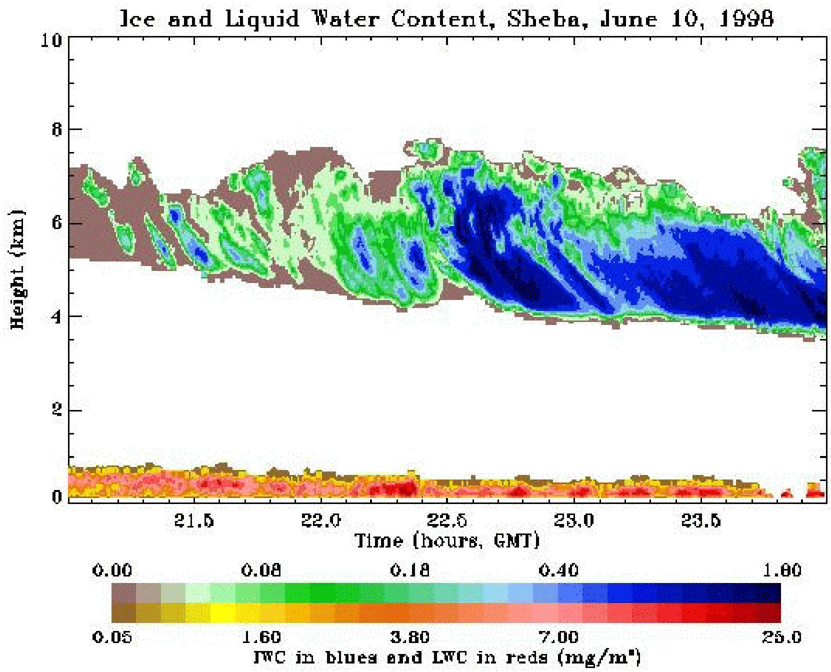

Figure 4

retrievals and produce NETCDF files of results. Figure 4 shows an example when both a liquid retrieval and a modified ice retrieval was run for two different layers of cloud. This system will be used to produce the daily cloud retrievals at the NSA for the lifetime of the TERRA satellite.

6) Statistical characterization of arctic clouds

Using existing data from the year long SHEBA program, we have initiated research to characterize arctic clouds. Our original focus has been the FIRE-ACE experiment period from April-July 1998 since that is the time during which there was an extensive aircraft campaign over the SHEBA ice camp. On of the most important results has been quantifying the percent of time that all-ice or all-liquid, single layer clouds were observed.

	Fractional Cloudiness	**All-liquid (single-layer)**	**All-ice (single-layer)**
April	93.1	4.2 (0.0)	21.3 (7.0)
May	88.0	23.2 (3.8)	17.6 (6.1)
June	87.8	18.4 (4.5)	23.4 (7.9)
July	93.9	23.2 (5.6)	15.0 (5.9)
All months	90.7	17.3 (3.5)	19.3 (6.7)

Table 1. Cloud type characterization, in percent of time, for the FIRE-ACE months. Fractional cloudiness is the total percentage of time clouds were observed by the radar. All other values are percentages of when clouds were

present (i.e. portions of the fractional cloudiness). Single-phase cloud percentages are shown for both liquid and ice clouds. Single-phase and single-layer cloud percentages are show in parenthesis (these are a subset of the single-phase clouds).

Since both ground-based and space-based retrievals of cloud microphysical and optical properties are generally optimized for these simple situations, it is necessary to assess how often they will be applicable in practice. As it can seen from Table 1, it can in fact be expected that more complex cases requiring more complex solutions will be necessary for the majority of the time for arctic clouds. Table 2 shows some statistical values of arctic clouds microphysical properties that have been determined for the FIRE-ACE experiment from ground-based remote sensing techniques.

Parameter	**Range**	**Mean**	**Median**
R_e (liquid)	3-20 μm	7.4 μm	6.9 μm
LWC (liquid)	0-0.7 g/m^3	0.1 g/m^3	0.06 g/m^3
N (liquid)	10-120 cm^{-3}	54 cm^{-3}	56 cm^{-3}
D_{mean} (ice)	7-300 μm	60 μm	46 μm
IWC (ice)	0-0.1 g/m^3	0.005 g/m^3	0.001 g/m^3

Table 2. Ranges, means, and medians for each retrieved parameter. Retrieved ranges are based on 99.9% of the data in order to remove extreme outliers.

SUMMARY

Techniques for combining surface based radar and radiometer data sets to provide estimates of cloud microphysical properties have been specifically adapted for the conditions we have observed in arctic clouds, and a effective GUI interface has been developed that will allow daily subjective retrievals of single phase and multi-phase clouds, in either single layer or multi-layer configurations. Examination of SHEBA data indicates that retrievals will be more problematic for liquid clouds then for ice clouds, and that the frequent occurrence of mixed phase clouds will necessitate a subjective retrieval process. In addition to cloud phase, particle sizes, cloud occurrence at different altitudes, and optical depths, we will also be producing information on cloud top temperatures and cloud top pressure. The actual retrieval process has been significantly delayed by the availability of radar data from the North Slope of Alaska DOE/ARM site, however, these issues are almost resolved at the time of this report. Because of the corresponding delays in the TERRA launch, and the cloud retrievals from MODIS and CERES, the delays in the surface retrievals have not been critical. The rapid ingest of similar data sets from SHEBA by the satellite community indicates that these North Slope of Alaska data sets will utilized in a timely manner by the CERES and MODIS research teams. Uttal has had discussions with Rossow, Key, Maslanik, Minnis, Francis, Scheweigar, Baum and Wiley about an integrated comparison between the surface data sets and satellite based retrievals of cloud properties in the Arctic for a number of satellite platforms and instruments. This should be a major focus of work in the 4th year of this project. The SHEBA data set has been used to begun the process of characterizing arctic cloud properties, this work will be continued with the data from TERRA and the North Slope of Alaska. We expect to continue ongoing and active collaborations with the Minnis group (CERES) and also have recently started cloud overlap and layering studies with Baum (MODIS). We have discussed doing comparisons with Marchand (MISR), however it appears that it will be some time before the MISR group will have resources to address cloud retrieval cloud issues. As already planned and specifically request, a web site with daily cloud retrievals from the North Slope of Alaska will be critical for near future EOS validation studies.

The following is a list of submitted, refereed publications which have been supported by this EOS validation project. A number of related conference articles reports and presentations are not listed, but available on request.

Cloud Water Contents and Hydrometeor Sizes during the FIRE-Arctic Clouds Experiment, Matthew Shupe, Taneil Uttal, Sergey Matrosov, and Shelby Frisch. (Submitted to the JGR special issue on FIRE-ACE)

Cloud Coverage during Fire-Ace derived from AVHRR data, Patrick Minnis, David Doelling, Venkatesan Chakrapani, Doublas Spangenberg, Louis Nguyen, Rabindra Palikonda, Taneil Uttal, Robert Arduini and Matthew Shupe (Submitted to the JGR special issue on FIRE-ACE)

Airborne Studies of Cloud Structures over the Arctic Ocean and Comparison with Retreivals from Ship-Based Remote Sensing Measurements, Peter Hobbs, Arthur Rango, Taneil Uttal and Matthew Shupe (Submitted to the JGR special issue on FIRE-ACE)

Annual Cycle of Arctic Cloud Geometry and Phase from Radar and Lidar, Janet Intrieri, Taneil Uttal, Matthew Shupe and Brandi McCarty (Submitted to the JGR special issue on SHEBA)

Retrievals of Vertical Profiles of Ice Cloud Microphysics from Radar and IR Measurements Used Tuned Regressions between Reflectivity and Cloud Parameters, Sergey Matrosov, JGR, Vol 104, D14, 16,741-16753, July 27, 1999.

The Use of Doppler Radar to Assess Ice Cloud Particle Fall Velocity-Size Relations for Remote Sensing and Climate Studies, Sergey Matrosov and Andrew Heymsfield, (Accepted, JGR).