Project Report
Validation of CERES Cloud Retrievals over the Arctic with Surface-Based Millimeter-Wave Radar
November 25th, 2003

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This final project summary is for the 5.5 year period from 1997 (Award Date September 17, 1997) to 2003 (Final Extension Date April 30, 2003) for an amount of $634,391.

Goals of this Proposal

The primary intent of this proposal was to process radar and radiometer data from the North Slope of Alaska DOE/Atmospheric Radiation Measurement (ARM) site to yield long-term, high resolution, measurements of cloud microphysical and optical properties that are optimized for Arctic conditions. The data set was designed to be useful for comparison with and validation of satellite retrievals of cloud properties from TERRA sensors (primarily MODIS and CERES with a lower emphasis on MISR). The three primary activities that were originally proposed in 1997 were:

- Produce long-term continuous data sets for the Arctic DOE/ARM site in Barrow, Alaska for Re, IWP, LWP, τ, ε
- Validate radar-based cloud retrievals with aircraft data taken during the NASA/Fire Arctic Clouds Experiment at SHEBA
- Use pre-existing radar data sets from low latitudes to determination autocorrelation scales to average single-site surface measurements for space-time matching with the CERES footprint

Additional activities that were proposed during 4th and 5th year extensions included:

- Develop a GUI interface for integrating data from radar, several radiometers and rawinsondes so that operational cloud retrievals could be produced from any DOE/ARM site (or sites with similar instrument suites).
- Develop a web site at NOAA/ETL which provides access to the NSA retrieved data sets, but will also serve as an integrated front door to Arctic research activities at NOAA/ETL, specifically linking EOS objectives to the NASA/FIRE-ACE program, ISCCP and the NSF/SHEBA and SEARCH programs.
- Make preliminary comparisons between surface based radar data sets and the retrieved cloud products produced by the MODIS and CERES science teams.

- Use profiles of cloud microphysical properties from the radar-radiometer retrievals to perform preliminary radiative transfer calculations with STREAMER type code to how vertical distributions of cloud properties affect radiative heating profiles.

- Improve calculations of optical depth for mixed phase clouds, as well as implement additional radar only (as opposed to radar-radiometer) retrieval techniques to increase the number of situations in which ground based retrievals can be implemented.

Accomplishments

Long-Term Data Sets

The primary task of providing long-term surface data sets for validation and comparison studies for the MODIS and CERES instruments has been achieved and a 3-year (2000, 2001, 2002) CD set has been produced and distributed to the research community.

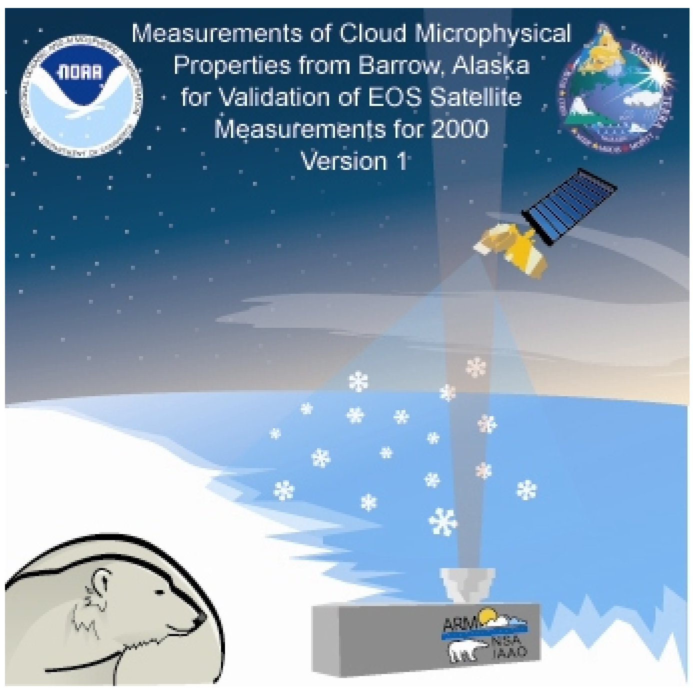

Figure 1 North Slope of Alaska Cloud Microphysics CD-set

The CDs provide graphical displays of classification masks, droplet/crystal sizes, ice and liquid water contents, input data stream, and version notes describing the different types of retrievals (with simplified equations that they can be easily applied to other data streams) and a comprehensive list of references. The version notes and references are included as an appendix to this report. Most importantly, the CDs also contain daily NETCDF files. It is expected that Version 2 of the NSA CD set will be released as a 5-CD set for (1999, 2000, 2001, 2002 and 2003) by March of 2004. It should be noted that there are unrecoverable and significant data gaps during the spring and summer of 2001, 2002 and 2003 due to interrupted operations of the DOE/ARM Cloud Radar at the NSA site.

Validate Ground-Based Retrievals with Aircraft Data

A number of studies have been conducted which compare the ground-based data with aircraft data. Comparisons of vertical profiles of size and water content in all-ice, optically thin, single layer cirrus clouds showed standard deviations of 25% and 50% respectively (Matrosov, et al., 2002). A second study (Zuidema et al., submitted 2003) showed that radar-based retrievals of cloud-ice in mixed phase clouds achieved good ice water contents and sizes, however, a study by Hobbs et al., 2001 indicated that radar-based liquid retrievals are not possible in the presence of ice crystals. Both the Zuidema and Hobbs results are as expected given the sixth order dependence of radar returns on particle size that results in ice crystals dominating the radar signal when ice and liquid droplets co-exist in the same radar measurement volume. These results support the Matrosov et al. (2002, 2003) suggestion that radar-only retrievals developed for all ice clouds are applicable to mixed-phase cloud volumes. The aircraft "validation" exercise has to some extent proven to be more of a comparison study as in has been clear that the absolute accuracies of the in-situ aircraft sensors also have substantial uncertainties. Without further statistical studies, it is not possible to assign absolute error bars to the radar-based retrievals. However, at the time of this report, best estimates by combining results from a number of studies indicate that retrievals for size and water content for liquid clouds are accurate within 13-33% and 15-45% respectively. The size and water content accuracies for ice clouds are within 25-45% and 50-85% respectively (Shupe et al, submitted 2003).

Determine single site averaging procedures to compare to satellite footprints

No significant progress has been made on this element. A limited number of case study comparisons have been attempted with unclear results. A height (wind speed/direction) dependant averaging protocol needs to be tested for a large number overpasses, however reprocessing and recalibration issues with both the satellite and surface data sets has delayed this element at the time of this report.

Develop GUI interface for cloud classification and retrievals

A sophisticated GUI system has been developed that allows rapid subjective analysis of a complex data stream from multiple instruments resulting in cloud scene classification masks and retrievals. This is a tool that could be also applied to radar-radiometer data sets from the Southern Great Plains and Tropical Western Pacific ARM sites. The GUI-based retrieval system was utilized during the NASA/CRYSTAL-FACE program allowing near real-time cloud retrievals that were posted on the web on a daily basis.

http://www.etl.noaa.gov/programs/2002/fireface/data/

Prior to CRYSTAL-FACE, this processing typically occurred several months after data was collected. At the time of this report, there are no other DOE or NASA groups using the ETL Cloud Classification and Retrieval GUI which is freely available. It is estimated that it would require about 1 week of training, and that a trained classifier could process radar-radiometer data to provide microphysical retrievals at a rate of about 2 weeks of data / day of processing. Some initial work has been done on developing an automated classification and retrieval system.

Develop a web-based gateway to NOAA/ETL Arctic cloud activities and results
The North Slope of Alaska cloud classification masks and retrievals of water path and particle sizes can browsed at:

http://www.etl.noaa.gov/et6/arctic

In addition to the data released on the NSA CD-set (200, 2001, 2002), the web site presently also has data for 1999 and 2003. This site also describes ETL activities related to the NSF Surface Heat Budget of the Arctic Ocean (SHEBA) program, and provides a 1-year data set of radar-radiometric cloud retrievals from the Arctic Ocean (October 1997-September 1998). A second link provides comprehensive ground-based data sets (lidar, radar, radiometer, surface meteorology, rawinsonde, ship reports, and cloud synopsis) for the NASA FIRE/ACE program. The most recent ETL/Arctic program linked is the Studies of Environmental Arctic Change (SEARCH) program. The ETL component of this interagency Arctic program will be to establish cloud-radiation-aerosol observatories in North-Eastern Canada and Siberia. Site visits have been made to Eureka and Alert, Canada. It is anticipated that the first instruments will be deployed in the summer of 2004 and that this site will contribute in the future to EOS validation data bases.

Make preliminary comparisons between surface-based and TERRA cloud products
A number of case study comparisons have been made between CERES Arctic-specific retrievals of cloud products from the MODIS instrument (team leader Patrick Minnis) and the radar-based measurements at NSA. The profiles of surface measurements have been averaged to provide layer-mean values, and some weighting strategies have been explored. For instance, layer-mean values are determined by weighting ice sizes with ice water contents to determine how cloud water mass as opposed to cloud optical depth affects the layer mean values of cloud properties viewed by MODIS.

Figure 2 shows the comparison of CERES cloud retrievals and ground-based radar radiometer retrievals for 9 all-ice overpasses during March 2001. This figure examines comparisons between ice water path, optical depth, IWC-weighted layer mean particle effective diameter, and the cloud height at which IWP is split evenly between the top half and the bottom half of the cloud. Comparisons in red are for all pixels in a 30x30km satellite footprint and 1 hour of surface data, with bars showing variability within these space (satellite) and time (radar) windows. In general, particle size appears to be the most successfully retrieved from the satellite, with ice water path showing some of the most significant variability.

A second procedure has been developed (Uttal et al., 2003) where profiles of retrieved extinction are determined and used to calculate cumulative cloud optical depth from

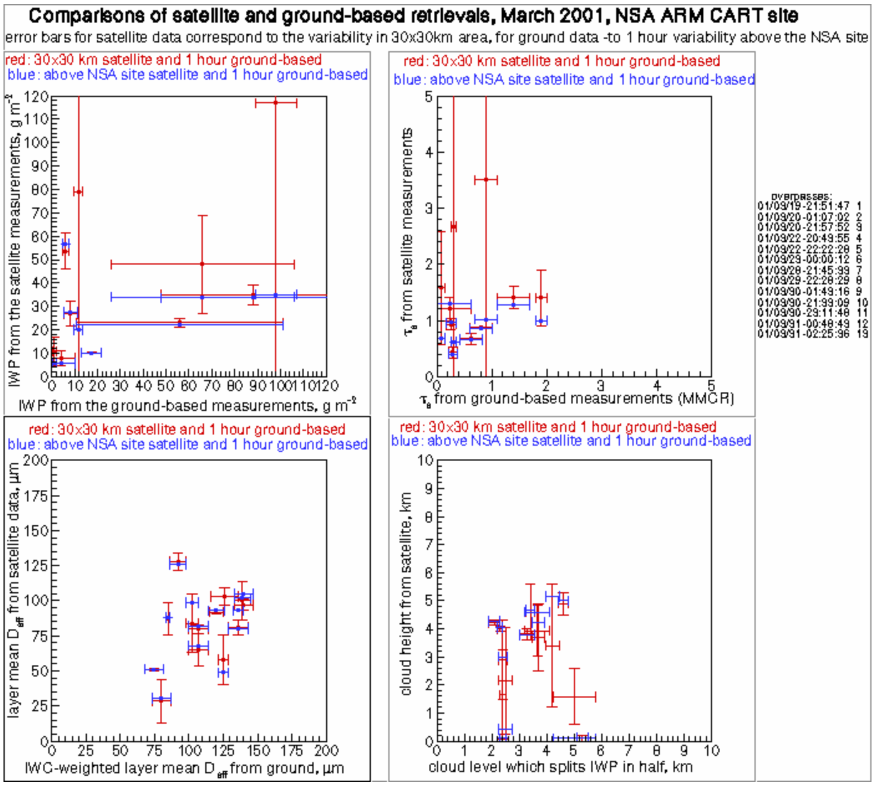

Figure 2 Ice Water Path, Optical Depth, IWC-weighted size and cloud height comparisons for March 2001, single layer all-ice clouds

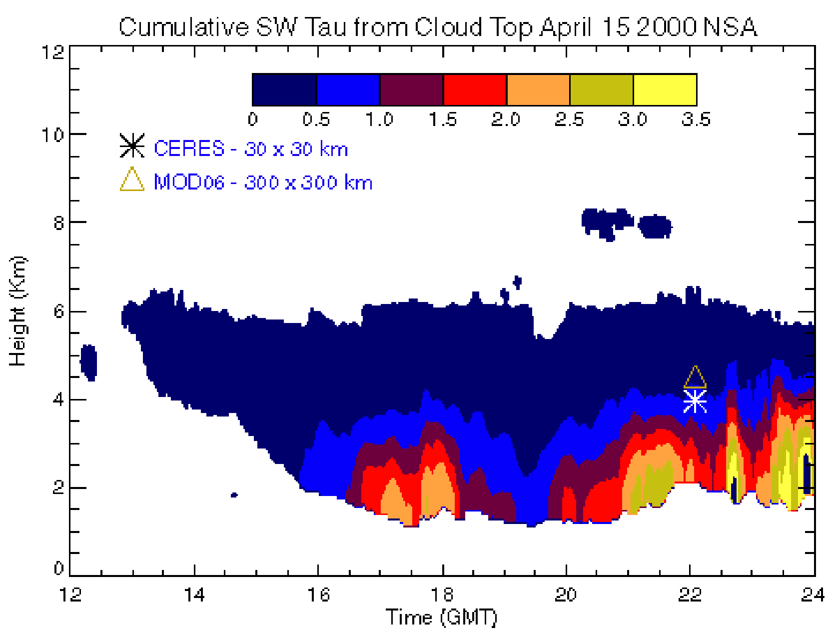

Figure 3 Cumulative short-wave optical depth calculated from cloud top using extinction profiles calculated from radar reflectivities. The star (30x30km) and diamond (3 km windstrip) at 22:05 GMT indicate estimates of cloud top height from the CERES-Team algorithm for MODIS.

cloud top. This method takes advantage of the vertically resolved cloud retrievals and provides an avenue for quantitatively assessing how satellite radiometric measurements perform for different cloud types. Figure 3 shows a how cloud top was detected by the MODIS sensor using CERES Team retrievals (modified for snow/ice surface conditions) relative to radar cloud top This case was for on April 15th at Barrow for an all- ice cirrus cloud. The cloud was geometrically thick, but optically thin and the upper 2 km (about 40% of the cloud depth) was particularly transparent, with an optical depth of only 0.5. The satellite values for cloud top suggest that the MODIS channels utilized were insensitive to the upper regions of the cloud where extinction was particularly low. At present, a number of cases have been compiled representing both night-time and day-time scenarios, for all-ice, all-liquid, single and multiple layer to further investigate the satellite performance.

<u>Perform preliminary analysis of how vertical distributions of cloud properties affect atmospheric heating profiles</u>

Profiles of explicit radar-derived microphysics have been input into the STREAMER radiative transfer package developed by Dr. Jeffrey Key at University of Wisconsin (Shupe et al., 2002 and Zuidema et al., submitted). Figure 4 shows how profiles and layer means of the radar-based crystal sizes result in radiative heating profiles that vary substantially from the profile resulting from an a priori fixed crystal size of 30 um (commonly used in model calculations).

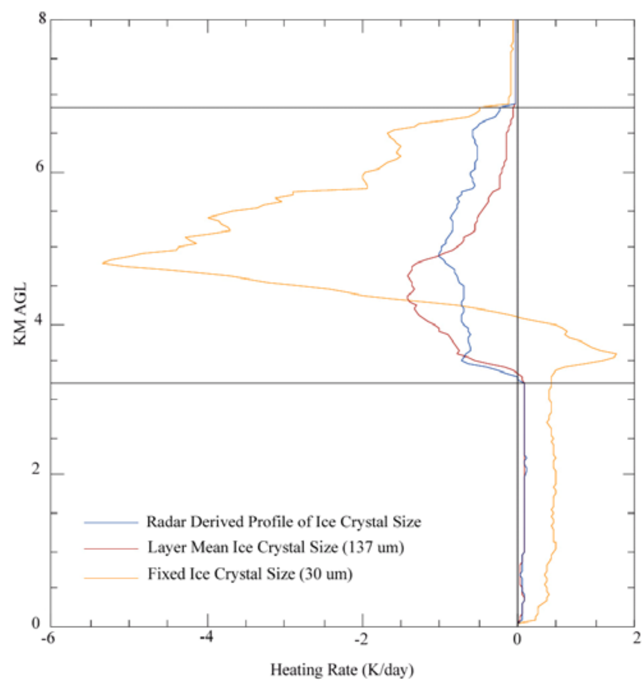

Figure 4 Profiles of Cloud Heating Rate Forcing (CHRF) for an ice cloud. Horizontal lines indicate cloud base and top. CHRF is defined as the difference between total calculated heating rate and clear sky heating rate.

Figure 4 suggests that if the satellite cloud algorithms can successfully retrieve layer-mean particle sizes that it will be a significant improvement over a priori assumptions. Zuidema et al (submitted) has further investigated compared radiative fluxes calculated with explicit microphysics profiles and measured radiative fluxes. The good agreement that resulted has further encouraged confidence in the radar-based data and retrieval techniques allowing determination of cloud forcing with a reasonable degree of reliability.

Improve arctic-specific radar-radiometer based cloud retrievals
A comprehensive suite of techniques have been developed which allows retrievals for all kinds of cloud scenes including ice, liquid, mixed-phase, precipitation and multi-layer. These procedures are described in Appendix 1 (attached). All retrievals are range resolved as opposed to layer averages. The radar is the only essential data stream, and more approximate retrievals can be utilized when radiometric data streams are interrupted or are unusable (for instance if low level liquid clouds radiometrically obscure upper level ice clouds). Radar-only retrievals fall into two categories: radar-reflectivity-based relationships with seasonally specific coefficients based on the more robust radar-radiometer relationships and/or in-situ aircraft data from the FIRE-ACE program.

A technique has been developed (Matrosov et al., 2003) that calculates ice cloud optical thickness and extinction estimates from the radar measurements. Because this technique utilizes only radar reflectivity and Doppler velocity, it can be applied to multi-cloud and mixed phase conditions. The resulting cloud optical parameters are important in determining the radiative impact of the clouds, and facilitate the kinds of surface-satellite comparisons demonstrated in figure 3.

Recommendations on how this project can be used to benefit EOS objectives
1) Adapt and implement the cloud classification and retrieval GUI at ARM sites and/or at sites with availability of similar radar and radiometer data sets. The retrieval GUI can be easily adapted to incorporate retrieval techniques developed by non-ETL groups. This will allow development of long-term cloud microphysics data sets for a number of sites that are not presently available.

2) The NSA data sets are now in sufficient order to facilitate multi-year statistical comparisons between TERRA, AQUA and surface measurements. It will be important to determine how monthly and annual trends compare on particle sizes, water contents, and frequency of occurrence of ice, liquid and mixed phase clouds, and cloud fraction. An important part of this task will to be generate statistics on cloud morphology and cloud forcing for the NSA data set similar to those that have been generated for the SHEBA data set.

3) Statistically determine the performance of the TERRA, AQUA cloud retrievals for a wide range of environmental (day, night, sun-angle, geographical location) and cloud conditions (single-phase, single-layer, multi-phase, multi-layer, optically thin, optically thick etc).

4) Fully utilize the vertical profile information from the surface sites to determine the performance of the TERRA AQUA cloud retrievals.

5) Implement correction/calibration algorithms that can 1) used to blend long-term (e.g AVHRR, TOVS) and modern (TERRA AQUA) satellite data sets to create long-term satellite-based cloud climate records.

Notes on Related Funding

The work performed for this EOS/NASA grant (Contract S-97895-F, Program Manager: David O'C Star) has been closely coordinated with FIRE/NASA (Contract L14997, Project Manager: Victor Delnore), NSF/SHEBA ((Grant # OPP-0084257, Program Managers Mike Ledbetter and Neil Swanberg) and the NASA/ISCCP Program (Contract # S-44788 Program Manager William Rossow). These projects had many over-lapping objectives, however, every effort was made to avoid redundant funding for the same activities. Additional detail can be provided on request.

Publications summarizing and acknowledging EOS work have included:

Hobbs, P. V., A. L. Rangno, M. D. Shupe, and T. Uttal, 2001: Airborne studies of cloud structures over the Arctic Ocean and comparisons with deductions from ship-based 35-GHz radar measurements, *J. Geophys. Res.*, **106**, 15,029-15,044.

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Matrosov, S.Y., M.D. Shupe, Andrew J. Heymsfield, Paquita Zuidema, 2003: J. Appl. Meteorl, 42, 1584-1596. (Note: Acknowledgement to the EOS program was inadvertently not included on this publication).

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Shupe, M.D., T. Uttal, S.Y. Matrosov, and A.S. Frisch, 2001: Cloud water contents and hydrometeor sizes during the FIRE - Arctic Clouds Experiment, *J. Geophys. Res.*, **106**, 15,015-15,028.

Shupe, M.D., S.Y. Matrosov, and T. Uttal, 2002a: An annual cycle of remotely-derived Arctic cloud microphysics, I: Retrieval techniques and assessment. *J. Appl. Meteor.*, submitted.

Shupe, M.D., T Uttal, and S.Y. Matrosov, 2002b: An annual cycle of remotely-derived Arctic cloud microphysics, II: Single-phase cloud results. *J. Appl. Meteor.*, submitted.

Uttal, T. 2001: Comparison of NSA Cloud Properties for April, May, June and July, 6th Conf. on Polar Meteorology and Oceanography, 14-18 May, Sand Diego, California.

Uttal, T. Sun-Mack S., P. Minnis and J. Key, 2003: Comparison of Surface AND Satellite Measurements of Arctic Cloud Properties, 7th Conf on Polar Meteorology and Oceanography.

Zuidema, P., B. Baker, Y. Han, J. Intrieri, J. Key, P. Lawson, S. Matrosov, M. Shupe, R. Stone, T. Uttal: The Characterization and Radiative Impact of Springtime Mixed-Phase Cloudy Boundary Layer observed during SHEBA, submitted to J. of Atmos. Sciences.

APPENDIX A – Material Provided on NSA Cloud Microphysics CD (Version 1)
This Appendix includes the Version Notes that are included on the first release of the NSA Cloud microphysics CD for 2000, 2001, 2003. Copies of the CD are available from Taneil.Uttal@noaa.gov

Acknowledgements

The funding for creating long-term, Arctic, cloud microphysical data sets was provided by the NASA Earth Observing Validation Program (Contract S-97895-F, Program Manager: David O'C Starr). The development of the different retrieval techniques that were applied were funded by a number of programs with contributions from the NASA/FIRE Arctic Clouds Experiment (Contract L14997, Project Manager: Victor Delnore), the NSF Surface Heat and Energy Budget of the Arctic (SHEBA) Program (Grant # OPP-0084257, Program Managers Mike Ledbetter and Neil Swanberg) and the Department of Energy, Biological and Environmental Sciences Program (Projects ER62342 and ER61960)

The radar, radiometer, and rawinsonde data sets were acquired from the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program (Director Wanda Ferrell) data archives, and were collected by instruments that are operated as part of the North Slope of Alaska operations of the DOE/ARM program. The ARM program has data sharing and distribution policies that should be reviewed at http://www.arm.gov as these cloud retreivals are derived completely from DOE/ARM data sets.

A large number of individuals have contibuted to this project through development of state-of-the-art instruments, retrieval techniques, programming support, discussions, data processing, managment of individual input data sets, and idea generation. In particular, the inputs of the following individuals are recognized: Bruce Weilicki, Matthew Shupe, Sergey Matrosov, Shelby Frisch, Eugene Clothiaux, Patrick Minnis, Bill Rossow, Louis Nguyen, Ken Moran, Ann Keane, Duane Hazen, Brad Orr, and Paquita Zuidema. Appreciation is extended to the DOE/ARM, in particular Kevin Widener, Mark Miller and Jim Liljegren.

The work described here was performed by the NOAA/Environmental Technology Laboratory. Comments, questions and suggestions should be directed to Taneil Uttal R/E/ET6, 325 Broadway, Boulder, Colorado 80305, or Taneil.Uttal@noaa.gov.

Retrievals are Retrievals, Not Measurements.

The most important thing to remember when using the cloud microphysical values on this CD is that they are observation-based-retrievals, not direct measurements. All of the retrievals use numerous assumptions. These may include such approximations as spherical ice particles, gamma, exponential, or lognormal droplet/ice particle size distributions, ice particle densities parameterized on particle size, and parameterization relating radar reflectivities to cloud properties based on aircraft data. It should also be considered that the radar-radiometer technique that utilizes the Liquid Water Path (LWP) from the microwave radiometer is a retrieval-based-on-a-retrieval, since LWP is itself retrieved from radiometric brightness temperatures.

Several studies have addressed the issue of errors associated with radar-based cloud retrievals. While not definitive, the ice retrieval uncertainties are expected to be 30-50% for particle size and 50-100% for ice water content and the liquid retrieval uncertainties are expected to be 20-40% for droplet size and 20-60% for liquid water content.

In the following sections, for cases where iterative or polynomial fits were not utilized, reduced equations have been provided to show how the cloud microphysics were calculated. However, it should be noted that these seemingly simple equations were derived through a complex line of reasoning, and the full derivations should be carefully examined in the references indicated.

Radar Data

All retrievals are based on continuous, vertically-pointing, 35-GHz radar data that was originally collected in 4 different operating modes with variable sensitivities optimized for different cloud and precipitation situations. Typically these modes cycle every 9 s, and data are collected at 45 m or 90 m range resolutions. The modes were optimally combined to a single radar product using the DOE/ARM ARSCL (Active Remotely-Sensed Clouds Locations) program, and interpolated to a 1 min-45 meter time-height grid. The existence of an ARSCL file does not necessarily indicate that the radar was operating on a given day. Thus, the measurements panel in the browser has a "No Radar Data" label on days when there was not a single pixel of radar return, which is considered to be unlikely even in clear sky situations. The radiometers often indicate cloudiness when there is no apparent radar return, and this filter can be additionally used to distinquish missing-data-days from clear-days. Existence of an ARSCL file with radar returns does not always guarantee reliable results, as an ARSCL radar file will be generated even if the radar was not operating optimally. Due to this ambiguity, there is an extended NO DATA period between April 1 and July 31 in 2001 when it is known that the radar was measuring degraded returns due to equipment problems. There may be other intermittent periods that have not been identified. A missing hyperlink in the dates menu indicates that no ARSCL file existed in the ARM archive for that day.

Radiometer Data

The microwave radiometer measures brightness temperatures at 23.8 GHz and 31.4 GHz. Starting on April 25, 2002 this CD utilizes LWP values that implement oxygen and water vapor absorption models that are more appropriate for the supercooled liquid clouds found in the Arctic. Prior to that date, the absorption coefficients were those developed for warmer, above freezing clouds (since the ARM program was still in the midst of updating the LWP data archive when this CD was the published). Studies have been conducted to investigate the magnitude of the difference. In general, it can be expected that the LWP values will be on the order of 15-20% less with the new absorption coefficients, with the offset increasing for smaller values of LWP. Note that this change in LWP retrieval coefficients can be expected to cause a corresponding offsets in any cloud microphysical retrievals that utilize LWP data derived from the microwave radiometer. Both the new and the old LWP retrievals are based on a statistical approach which utilizes a climatological set of rawinsonde measurements. A more accurate approach would be to use radar data to derive liquid water-weighted cloud temperature as described by Liljegren et al. (2001). The error in the absolute LWP values is about 25 g/m^2 (Westwater et al. 2001).

To determine infrared cloud brightness temperatures, the spectral measurements from the Atmospheric Emitted Radiance Interferometer (AERI) were integrated over 10.96-11.27 microns.

Cloud Classification

Classification of cloud scenes into 7 categories ("ice", "simple-ice", "liquid", "simple-liquid", "mixed", "drizzle", "rain", and "snow") was based on visual inspection of radar reflectivity, Doppler velocity, Doppler spectral widths, microwave and IR radiometer data, and rawinsondes. This subjective classification was independently checked and rechecked. "Ice" and "liquid" classifications indicate that radar-radiometric retrievals were possible (radar + IR radiometer for ice, radar + microwave radiometer for liquid). "Simple-ice" and "simple-liquid" classifications indicate that retrievals are based on radar data only, either because radiometers were obscured by multiple cloud layers, radiometric data was unavailable, or in the case of ice, the clouds were optically thicker than ~6.

In many cases, the clouds are classified as mixed-phase, indicating that both ice and liquid appeared to exist simultaneously in a cloud layer. In general, the liquid tends to exist in discrete layers; however, for the purposes of classification, the entire layer is considered to be mixed-phase and no effort is made to place the liquid. Because the radar reflectivity is dominated by the larger ice crystals, the only retrievals implemented in the mixed-phase cloud regions are the non-radiometric ice retrievals. Depending on the application, these retrievals should be used cautiously since the neglected liquid component may contribute to uncertainty in the retrieved ice properties and it may be the most important phase in determining the cloud radiative properties.

In addition to in-cloud temperatures and LWP from the microwave radiometer, Doppler spectral widths have been used as a qualitative indicator that clouds may be mixed-phase. This is based on the rational that increased spectral widths (indicating a wider spread in the distribution of vertical velocities) may indicate a wider range of hydrometeor sizes (fall velocities) which might occur if water droplets and ice crystals were mixed in the same volume. This is not a fully researched topic; however, preliminary insitu aircraft comparisons as well as intercomparison between coincident depolarization lidar data with radar spectral widths at SHEBA indicate that this is not an unreasonable assumption. The other candidate for producing increased spectral widths is turbulence. The relationship between turbulence and the development of mixed-phase layers is another topic of ongoing research

Precipitation classifications were most often done on the basis of the radar mean Doppler velocities. Drizzle was characterized by fall speeds that were typically larger than ~0.2 m/s and reflectivities higher than -15 dBZ. Rain was most often indicated by a clear melting layer signature (bright band) in the radar reflectivities, and velocities greater than ~2 m/s.

The netcdf files contain a mask field that indicates which retrievals were run at any given location in a cloud time-height scene. The classification codes are described below. Note that some of the equations below utilize "dBZ" (radar reflectivity factor) and some utilize "Z" (radar reflectivity in units off mm^6/m^3). Z is related to dBZ by the equation: Z=10^(dBZ/10).

Precipitation Retrievals

CLASSIFICTION CODE 1 - RAIN

The RAIN retrievals assume the Marshall-Palmer drop size distribution and Rayleigh scattering conditions (which may at times be violated at K-band).

RainRate = 10^((dBZ-23)/16) [mm/hr]
RainDropSize = 244-RainRate^(0.21) [microns]
RainWaterContent - 0.072 * RainRate^(0.88) [g/m^3]
RainDropConcentration = 0.00195*RainRate^(0.21) [1/cm^3]

CLASSIFICATION CODE 2 - SNOW

The SNOW retrievals assume the Gunn and Marshal snow size distribution.

SnowFallRate = 10^((dBZ-14.5)/9.5) [mm/hr]
SnowFlakeSize = 392*SnowFallRate^(0.48) [microns]
SnowWaterContent = 0.25*SnowFallRate^(0.9) [g/m^3]
SnowFlakeCondentration = 0.00149*SnowFallRate^(-0.39) [1/cm^3]

Liquid Retrievals

CLASSIFICATION CODE 3 - LIQUID CLOUD, RADAR ONLY METHOD

The radar-only LIQUID retrievals assume a lognormal droplet size distribution with a width of 0.31 (Frisch et al. 2002).

LiquidWaterContent = c*Z^(0.5) [g/m^3]
DropletEffectiveRadius = d*Z^(0.166) [microns]

c = (pi/6)*exp(-0.432)*N^(0.5)
d = 50*exp(-0.048)*N^(-0.166)
N = 75 cm^(-3) OR N is determined by a polynomial fit to reflectivity determined using aircraft measurements.

CLASSIFICATION CODE 4 - LIQUID CLOUD, RADAR-ONLY AS WELL AS RADAR + MICROWAVE RADIOMETER METHODS

All Code 3 retrievals are implemented in addition to a radar-radiometer technique that utilizes the microwave radiometer-derived LWP scaled by radar reflectivity profiles to distribute liquid water contents in cloud (Frisch et al. 1995).

CLASSIFICATION CODE 5 - DRIZZLE

At present no drizzle retrievals are implemented.

Ice Retrievals

Note that there is not currently a standard ice crystal size definition across the research community. All retrievals utilized here derive the mean diameter which characterizes the assumed exponential distribution of physical particle sizes. The mean diameter is related to the median volume diameter by: MeanDiameter=MedianDiameter/3.54 for the exponential particle size distribution. For the ice particle sizes plotted in the "Particle Size" browser panel, ice particle diameters are converted to effective radii to be consistent with the measurement units for the cloud droplet sizes. The equations used for the conversion are:

EffectiveRadius = 13.74*(MeanDiameter)^0.3 for MeanDiameters >= 23.7 microns
EffectiveRadius = 1.5*(MeanDiameter) for MeanDiameters < 23.7 microns

CLASSIFICATION CODE 6 - ICE CLOUD - RADAR-ONLY METHODS

METHOD 1
The radar-only, empirical ICE retrieval method uses:

IceWaterContent = a*Z^b [g/m^3]
MeanDiameter = 40.5*a^(-0.53)*Z^((0.53(1-b)) [microns]

a = monthly values of "a" were determined from periods during which Radar-Radiometer method (See CODE 7) was implemented on single layer, optically thin ice clouds
b = 0.63

METHOD 2 (Matrosov et al., 2002)
The radar-only, Doppler velocity-reflectivity ICE retrieval method is appropriate for MeanDiameter >15 microns.

MeanDiameter = determined by particle characteristic size - fall velocity relationships over 20 min averages of Doppler velocity measurements [microns]
IceWaterContent = 1100*Z/(MeanDiameter)^(1.9)) [g/m^3]

CLASSIFICATION CODE 7 - ICE CLOUD, RADAR-ONLY METHODS AS WELL AS RADAR + IR RADIOMETER METHOD

All Code 6 retrievals are implemented in addition to a radar-IR radiometer ICE retrieval method that uses AERI-derived brightness temperatures to tune the coefficient "a" (Matrosov et al., 1999). The tuned method is good for MeanDiameters greater than about 15 microns.

IceWaterContent = a*Z^b [g/m^3]
MeanDiameter = 40.5*(Z/IceWaterContent)^(0.53) [microns]

b is scaled linearly through cloud height with a value of 0.7 at cloud base and 0.55 at cloud top
a = determined iteratively from AERI brightness temperature measurements.

CLASSIFICATION CODE 8 - ICE AND LIQUID PRESENT IN CLOUD LAYER

CODE 6 ICE retrievals are implemented.

CLASSIFICATION CODE 9 - UNCERTAIN
CODE 6 ICE retrievals are implemented.

Calculations of Optical Depth

Calculations of optical depth are not straight forward due to the frequent occurrence of multiple cloud layers (often ice, liquid and mixed-phase combined), and a prevalence of radiometrically thick cloud layers. To approximate a combined optical depth for the total cloud column, the following procedure is used:

For Liquid Layers: The microwave radiometer value of LWP is used if available, otherwise the LWP from the code 3 radar retrieval is calculated by summing the retrieved LWC. The CODE 3 output is used in both cases to determine a layer-mean, LWC-weighted droplet effective radius. For mixed-phase clouds and drizzle regions, the layer-mean DropletEffectiveRadius is assumed to be 10 microns. OpticalDepth is then calculated using:

OpticalDepth (Liquid) = LWP*(0.029+1.3/DropletEffectiveRadius)

For Ice layers: The IWP is calculated by summing the IWC and obtaining layer-mean, IWC-weighted ParticleMeanDiameter from CODE 6, Method 1. OpticalDepth is then calculated using:

OpticalDepth (Ice)= IWP*(0.021+1.27/ParticleMeanDiameter)

TotalOpticalDepth = OpticalDepth (Liquid) + OpticalDepth (Ice)

Future Work

Future versions of this data set will include:
Processing of data for 1998, 1999, 2003 and future data sets.
Implementation of drizzle retrievals.
Implementation of new LWP values prior to April 25, 2002 as they become available..
Implementation of more current precipitation retrievals for 35-GHz radar.

Contact

The development of this data set has been a long complex process. Comments, suggestions, and/or identification of errors are much appreciated and should be directed to Taneil.Uttal@noaa.gov.

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