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COMPARISON OF SURFACE AND SATELLITE MEASUREMENTS OF ARCTIC CLOUD PROPERTIES

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1. INTRODUCTION

Clouds have large impacts on the Arctic surface radiation budget, and the ability to measure and interpret their microphysical and optical properties is a necessary precursor to understanding cloud influences on the Arctic climate system. Because of the remoteness and inaccessibility of the Arctic, satellite observations provide the only feasible means of Arctic-wide observations, and it is fortuitous that measurements with the potential for determining Arctic cloud properties extend back to 1978. At the same time, because of the special challenges posed by the long polar nights (rendering visible channels unusable) and bright, underlying snow and ice surfaces (often making cloud identification difficult), the potential of these satellite records have not been fully utilized either to study cloud variability or to develop Arctic cloud climate indices.

Since 1998, the Department of Energy/Atmospheric Radiation Measurement (DOE/ARM) program has operated an extensive suite of surface-based active and passive remote sensors in Barrow, Alaska that are designed to observe the microphysical and radiative properties of clouds. In particular, a 35 GHz radar (Moran et al., 1998) provides the basis for a number of cloud retrieval techniques that result in vertical profiles (0-12 km AGL with 45 m range resolution) of cloud properties

In this paper, a methodology is presented to compare surface and satellite measurements that takes advantage of vertically resolved cloud property retrievals from the Barrow site. The motivation for this study is to be able provide the capability to quantitatively assess how satellite radiometric measurements interact with different cloud types and how common conditions such multiple layers systems, mixed phase scenes and low sun angles, will affect satellite cloud retrieval performance.

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The satellite retrievals used for the case study example are the CERES (Cloud and Earth's Radiant Energy System) science team retrievals that use the MODIS instrument on the Terra satellite, and Polar Pathfinder data sets that use the AVHRR (Advanced Very High Resolution Radiometer) instrument on the NOAA Polar Orbiting Satellites.

2. BACKGROUND

Retrieval techniques for various combinations of radar, infrared and microwave radiometric measurements have been developed for a wide range of cloud scenes including all-ice, all-liquid, mixed-phase and multiple layers. A brief summary is presented in Shupe et al., (2001). The most powerful aspect of these techniques is that because they are based on range-resolved, active radar measurements it is possible to obtain profiles of ice water content (IWC) and ice crystal sizes (D_m) as well as integrated or geometrical properties such as ice water path (IWP) and cloud boundaries. These techniques are being applied to a multi-year data set (1998 to present) collected by instruments operated by DOE/ARM in Barrow, Alaska. Retrievals are also available for the year-long SHEBA (Surface Heat and Energy Budget of the Arctic Ocean, Uttal et al. 2002) field experiment (1997-1998) that was conducted in the Arctic Ocean. In combination, the two data sets provide a substantial opportunity for validation of satellite cloud retrievals in the Arctic and a number of studies (Minnis et al., 2001, Key and Intrieri, 2000, Spangenberg et al., 2002, Dong et al., 2001) have made comparisons of satellite measurements to layer mean averages of cloud properties from surface radar-based retrievals.

Recently, a method has been proposed to determine short-wave optical depth and extinction profiles from radar and/or radar-radiometer based measurements (Matrosov, et al, submitted). This method for inferring cloud optical properties from the radar greatly increases it's utility in addressing situations when and where calibrated lidar measurements are not available.

3. SENSORS AND RETRIEVAL TECHNIQUES

3.1 Ground-Based Radar Retrievals

The Matrosov et al. (submitted) method extends the work described by Matrosov et al., (1999) and Matrosov et al., (2002) and proposes 3 techniques to estimate ice cloud optical thickness/extinction from radar-only or combined radar-radiometric measurements. Method 1 utilizes a empirical method relating extinction to radar reflectivity alone. Method 2 utilizes additional measurements from infrared and microwave radiometers, as well as temperature profiles from soundings. While this is the most robust method, it requires that all of the sensor inputs are available, the cloud must be optically thin, and the ice cloud of interest must be unobstructed by low level liquid clouds. The third method utilizes Doppler velocities in combination with radar reflectivity to constrain ice particle sizes; this method is confined to cases where atmospheric turbulence or convection is not likely to be a significant factor. For this paper, method 1 has been utilized since it is the most versatile in terms of cases to which it can be applied. However it should be kept in mind that the absolute accuracy is a function of successfully determined regression coefficients. Comparison of the 3 techniques and evaluation of errors is a subject of research in progress.

3.2 AVHRR Satellite Retrievals

Retrievals from the Advanced Very High Resolution Radiometer (AVHRR) utilize the AVHRR Polar Pathfinder (APP) dataset (Maslanik et al., 1998). The APP product consists of twice-daily composites of satellite overpasses at 4:00 and 14:00 local solar time, with most of the observations falling within one hour of those times. The standard APP product suite has been expanded to include cloud optical depth, cloud top pressure, cloud top temperature, cloud phase, cloud particle effective radius, radiative fluxes, and cloud radiative forcing on a 25 km scale, sub-sampled from 5 km pixels (hereinafter called “APP-x”). Clouds are taken to be composed of liquid water droplets or ice particles; mixed phase clouds are not considered. Cloud detection is done with a variety of spectral and temporal tests optimized for high-latitude conditions. Cloud particle phase uses near-infrared reflectances (daytime) and infrared brightness temperature differences to separate ice and liquid ("water") clouds (Key and Intrieri, 2000). Daytime cloud optical depth and particle effective radius retrievals use absorbing (3.7 µm) and non-absorbing (0.9 µm) wavelengths, where the absorbing wavelength is more sensitive to particle size and the non-absorbing wavelength is more sensitive to optical depth. Nighttime retrievals utilize radiances at 3.7, 11, and 12 µm. For additional algorithm details, see Key (2002).

3.3 CERES Satellite Retrievals

The CERES team retrievals over snow use the solar-infrared near-infrared technique (SINT) that employs the MODIS Instrument 3.75, 10.8, and 1.61-µm channels, respectively, to derive cloud particle size, temperature, and optical depth (Minnis et al. 2002). The SINT is an adaptation of the method developed by Platnick (2001). The technique relies on the 1.6-µm channel to derive optical depth and has been shown to estimate optical depths in water clouds more accurately than the 0.65-µm channel over snow backgrounds (Dong et al. 2001). It has had minimal testing for ice clouds over snow.

4. RESULTS

Figure 1 shows general cloudiness over the North Slope of Alaska on April 15th, 2000. The cloud mask and particle phase classifier correctly identify an all-ice, single layer cloud system over Barrow. Cloud coverage was not particularly continuous in the region immediately over and around Barrow.

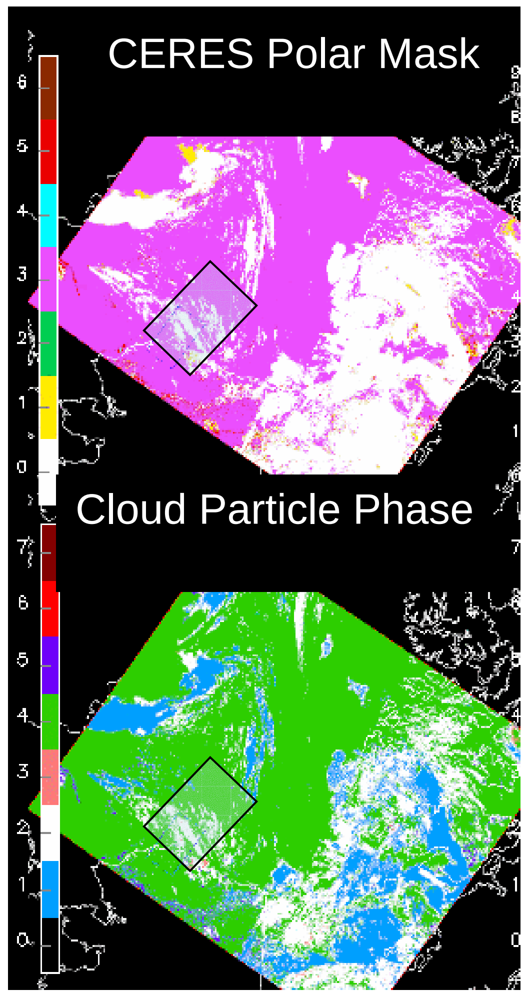

Figure 1 – Upper Panel: Cloud Mask, pink = ice/snow, white=cold cloud. Lower Panel Cloud Phase Classifier, green=clear, white=ice cloud, blue=water cloud. Box over Barrow, Alaska site is 100 km x 100 km.

Figure 2 shows a time-height cross section of the radar reflectivity and retrieved values of integrated liquid water path from the microwave radiometer. The cloud coverage immediately over the site was continuous after 13 GMT, and liquid water amounts were less than 20 g/m^2 which is below the reliable detection threshold of the instrument, indicating an all-ice cloud. The heavy red line at 22:05 GMT, and the dashed line at 23:45

GMT indicates the overpass times for the TERRA satellite and the NOAA polar orbiting satellite respectively. Comparison satellite retrievals were calculated for these times

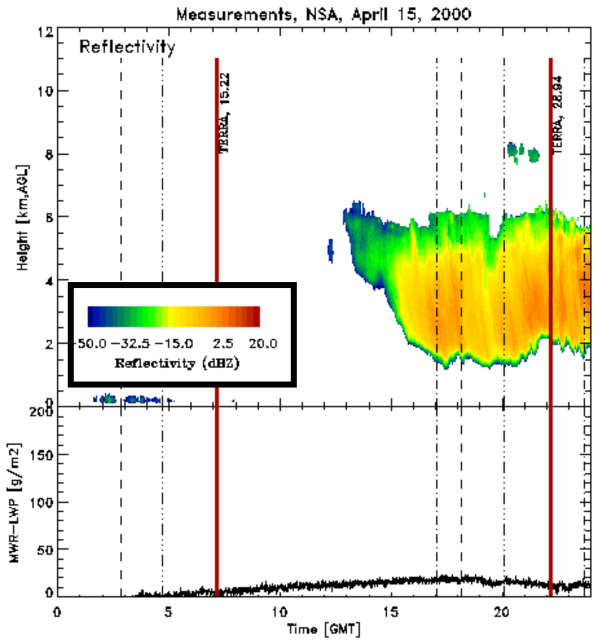

Figure 2: Top: Time-Height Cross Section of radar reflectivities . Bottom: liquid water path from a microwave radiometer. Red lines show overpass times for TERRA; dashed lines show overpass times for NOAA-12, NOAA-14, NOAA-15 and NOAA-16.

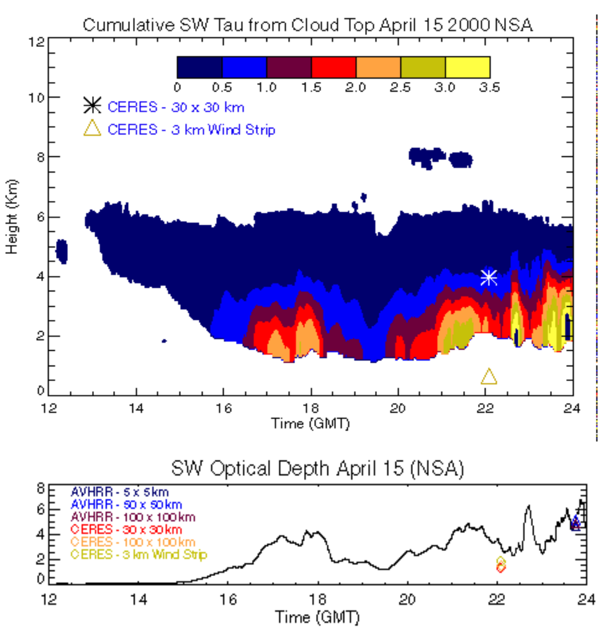

Figure 3: Top: Cumulative short-wave optical depth calculated from cloud top using extinction profiles calculated from radar reflectivities. The star and diamond at 22:05 GMT indicate estimates of cloud top height from the CERES retrieval. Bottom: Time series of SW optical depth from radar retrieval. Satellite retrievals of optical depth indicated at 22:05 GMT (CERES - diamonds) and 23:45 GMT (AVHRR - triangles).

Layers of cumulative-short-wave-optical-depth-from-cloud-top were calculated from extinction profiles generated by the Matrosov et al. (submitted) technique (Figure 3) for the April 15th 2000 case. The cloud system on this day was optically thin with a maximum optical depth of around 4.0. Between 13:00-16:30 GMT and 18:30-20:00 GMT, the optical depth did not exceed 1.5. The upper 2 km (about 40% of the cloud depth) of the cloud was particularly transparent, with a optical depth of only about 0.5. The cloud top heights are shown from the CERES-team cloud retrieval for a 30 x 30 km box (asterisk at 3.95 km AGL) and for a 3 km x 3 km wind-strip at (diamond at 0.64 km AGL).

The 30 x 30 km satellite cloud top height estimate suggests that the MODIS channels utilized were insensitive to the upper regions of the cloud where extinction is particularly low, the 3 km x 3 km wind-strip value is somewhat more difficult to interpret. The wind-strip value the result of additional processing that advects the individual pixels in the satellite granule based on cloud top and cloud center heights (provided by the ground sensors) and profiles of winds from the ECMWF. This exercise is an attempt to obtain a more exact match between the satellite pixels and the surface measurements. The cloud temperature retrieved by CERES for the wind strip data was actually 2 degrees Kelvin colder than that from the 30x 30 km box, suggesting that the cloud top height would have been closer to that observed by the radar. However, the retrieved height was dramatically lower; this discrepancy suggests that the particular ECMWF profile used for the wind-strip pixels included a strong surface inversion that was not found in the profiles used for most of the pixels in the 30 x 30 km box results. This aspect of the specified profile often causes problems with cloud height assignment for low clouds retrieved from infrared satellite data. Compilation of radar-satellite retrievals comparisons like that in Fig. 3 will aid the development of improved methods for retrieving the proper low-cloud heights from the satellite imagery.

In the lower panel of Figure 3 the satellite optical depths do not vary significantly as a function of averaging area (5x5 km, 50x50 km and 100x100 km for AVHRR, and 30x30 km, 100x100 km and 3 x 3 km for CERES); and the trend of increasing of optical depth between 22:00 and 24:00 GMT (as indicated by the radar) are captured by the CERES and AVHRR satellite retrievals.

In Figure 4, averages of IWP have been calculated for the cumulative-SW-optical-depth-defined -ayers (0-0.5, 0-1.0, 0-1.5, 0-2.0, 0-2.5, 0-3.0 and 0-3.5) shown in Figure 3. Comparison with the satellite retrievals indicates that both the CERES and AVHRR retrievals underestimate ice water path by about 50%, although as with optical depth, the general trend of increasing ice water path is measured by the satellite sensors.

Finally, in figure 5 layer averages of crystal sizes are calculated in the cumulative-SW-optical-depth-defined layers, This figure indicates that compared to IWP, the layer-mean sizes do not vary much as a function of optical depth from cloud top height. Indeed, because typical ice crystal size profiles which often decrease near cloud base (Shupe et al., 2001), it is possible for the layer mean size to be smaller when averaged through a greater depth of the cloud.

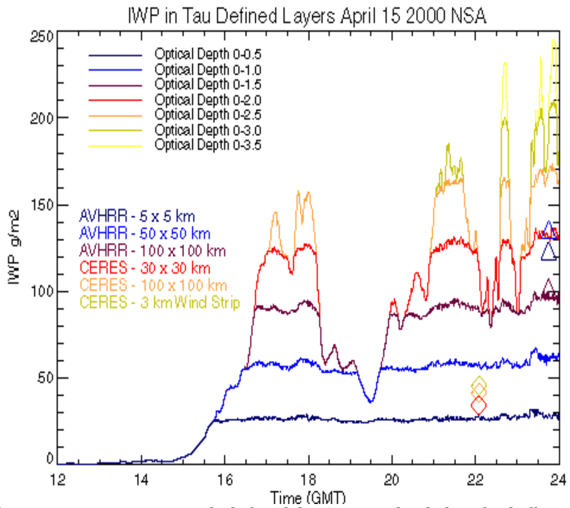

Figure 4: Ice water path (g/m2) in SW optical depth defined layers as shown in Figure 3. Integrated ice water path from CERES and AVHRR are indicated at 22:05 GMT (CERES - diamonds) and 23:45 GMT (AVHRR - triangles).

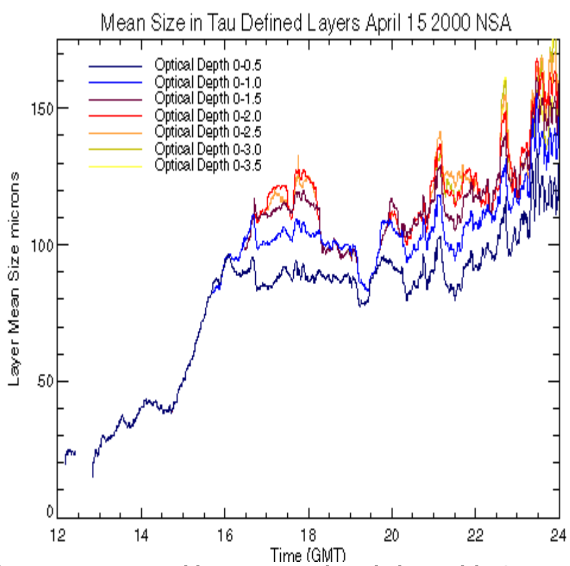

Figure 5: Ice crystal layer mean sizes (microns) in SW optical depth defined layers as shown in Figure 3.

5. DISCUSSION

This paper presents a methodology by which ground-based profiles of radar-based retrieved cloud properties can be used to develop sensible layer averaging schemes for such cloud properties as water path and ice crystal sizes. In this example, layer averages of ice water path and sizes were based on cumulative optical depth defined layers. This methodology, when applied to a sufficient number of cases, provide a basis for determining how satellite cloud retrievals perform for clouds of variable optical thickness, mixed phases, multiple layers, and different surface conditions.

In this preliminary case study, the CERES retrievals based on the MODIS instrument on TERRA, and the Polar-Pathfinder retrievals based on the AVHRR instrument on the NOAA satellite appear to produce consistent retrievals that capture trends in ice water path and optical depth. While it is not possible to draw general conclusions from this single comparison, it appears that there may be some important AVHRR and MODIS insensitivities to upper, optically thin portions of the cloud. It is unlikely that these parts of the cloud contain sufficient ice water mass to affect the net radiative fluxes of the cloud, but it may significantly impact the retrieval of such parameters as cloud top heights. This will be investigated with additional case studies using the methodology of defining averaging layers with the cumulative optical depth from cloud top.

6. ACKNOWLEDGEMENTS

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