RESULTS FROM THE ARM CLOUD RADARS

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1. INTRODUCTION

The Atmospheric Radiation Measurement (ARM) Program (Stokes and Schwartz, 1994) now operates ground-based remote sensing instruments at four sites in three locales. The first of these sites, the Southern Great Plains (SGP), was established in north central Oklahoma in the 1993. The second locale, the Tropical Western Pacific, contains two sites, one at Manus Island in Papua New Guinea and one at Nauru. The third is the North Slope of Alaska located at Barrow, Alaska. The essential suite of instruments at each of these sites was completed with the addition of a millimeter-wavelength cloud radar (MMCR). The first MMCR was installed at the SGP site in late 1996. The MMCR operates at a frequency of 35 GHz (a wavelength of 8 mm) in a vertical staring mode. It acquires measurements of radar reflectivity and pulse-pair Doppler velocity in four different modes with a range resolution of either 45 or 90 meters. Details of the radar operation can be found in the articles by Clothiaux et al. (1999a, 1999b).

In addition to the MMCR, each site is equipped with a suite of surface radiometers measuring all components of the surface radiation budget. A microwave radiometer is used to measure both the column water vapor path and liquid water path. An emittance interferometer is used to measure the nadir radiance between 5 and 20 microns. Cloud base height is measured with a micropulse lidar (MPL) system. The multi-filter rotating shadow-band radiometer (MFRSR) was used to measure aerosol optical depth. Standard meteorological sensors are used to measure surface temperature, humidity, and winds. Also, each site is equipped with a balloon-borne sounding system. The SGP site has a considerably more extensive selection of instruments including the only continuously operating Raman lidar system.

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2. CLOUD CLIMATOLOGY

The combination of the MMCR with other instruments allows us to derive a variety of interesting properties of clouds. The fact that the instruments are continuously operating allows us to create a climatology of cloud properties in a manner that has previously not been possible. In this section, we consider several examples of these products. Because the MMCR data has only been available for a few years, the sample period for these products is currently limited. We do, however, expect to extend them in the future.

Cloud Occurrence. Previous cloud occurrence statistics have been biased by the inability to see clouds throughout the depth of the atmospheric column. Thus ground-based observers tend to underestimate the occurrence of high level clouds, while satellite climatologies underestimate the occurrence of low clouds. Using a combination of the SGP MMCR and MPL, we have automated a cloud detection algorithm that allows us to determine the occurrence of clouds throughout the depth of the atmosphere. Given the sensitivity of the MMCR and comparisons between radar and lidar detection of thin single-layer cirrus, we estimate that we detect better than 95% of all high level clouds overlying low clouds. The initial data set consists of cloud detection (yes/no) in bins that have a vertical resolution of 90 m and a time resolution of about a minute. This detection set is then converted into a frequency distribution as a function of height and meteorological season for two years (Figure 1; Marchand et al., 2000). We can clearly see both intra-annual and interannual variations in this short record. For example, the summer seasons show an increase in the height of the highest clouds and a fairly clear demarcation of a high cloud layer (particularly in 1997). This is consistent with the increased incidence of deep convection over the SGP region during the warm season. The winter seasons show a greater incidence of overall cloud, particularly at midlevels. This probably reflects the occurrence of synoptic systems with deep clouds extending through much of the troposphere. The winter of 1998 shows a large increase in the

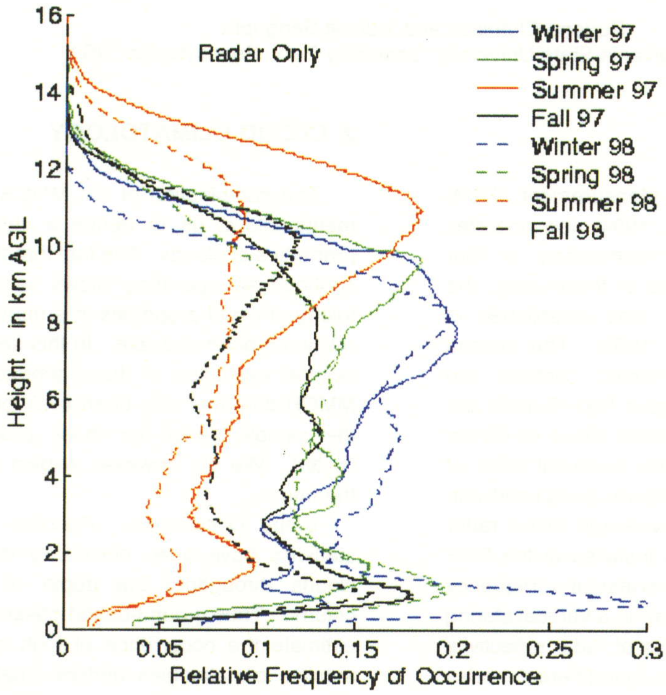

Figure 1. Frequency of Occurrence of Cloud Detected by MMCR at the ARM SGP Site. Similar results are obtained using a combination of radar and lidar.

occurrence of low clouds. This increase is directly related to the large El Niño event that occurred in 1997-98. This event enhanced the moisture flow into the SGP region, which produced more boundary layer cloudiness.

Surface Cloud Effect. One of the principal reasons that ARM studies clouds is to understand their effect on the surface radiation balance. We can quantify this effect by taking the ration of the measured downwelling solar irradiance at the surface to the clear-sky solar irradiance. The latter term is the amount of solar radiation that is received at the surface for cloud-free conditions and depends on the water vapor column concentration and aerosol optical depth. Rather than compute this term, which can then lead to issues over the agreement between observation and models, we have developed a technique (Long and Ackerman, 1997) that determines the cloud-free radiance from the measurement series. We first find all daytime cloud-free periods that are at least 2 hours in length. The measured irradiance during these periods is fit with a simple power law function of the cosine of the solar zenith angle. The coefficients of these fits are linearly interpolated across cloudy times to provide the cloud-free irradiance. This approach guarantees that our cloud effect ratio is independent of any model deficiencies or instrument biases and equals 1 during cloud-free conditions. We have carried out this analysis for a four-year from 1995 through 1998 and created monthly histograms of the results using bins of width 0.1 centered at 0.1, 0.2, etc. (Figure 2). All months show that the most likely value is 1. The colder months show a tendency for a "U" shaped distribution, reflecting the typical fractional cloud cover distribution that has maximal values for clear and overcast and a minimal values around 0.5. This is consistent with the passage of synoptic systems that tend to produce overcast sky separated by periods of clear. The warmer months show a monotonic decrease in frequency with decreasing cloud effect ratio. This probably is associated with an increase in broken cloud fields during the convective system and relatively infrequent cases of thick, overcast clouds.

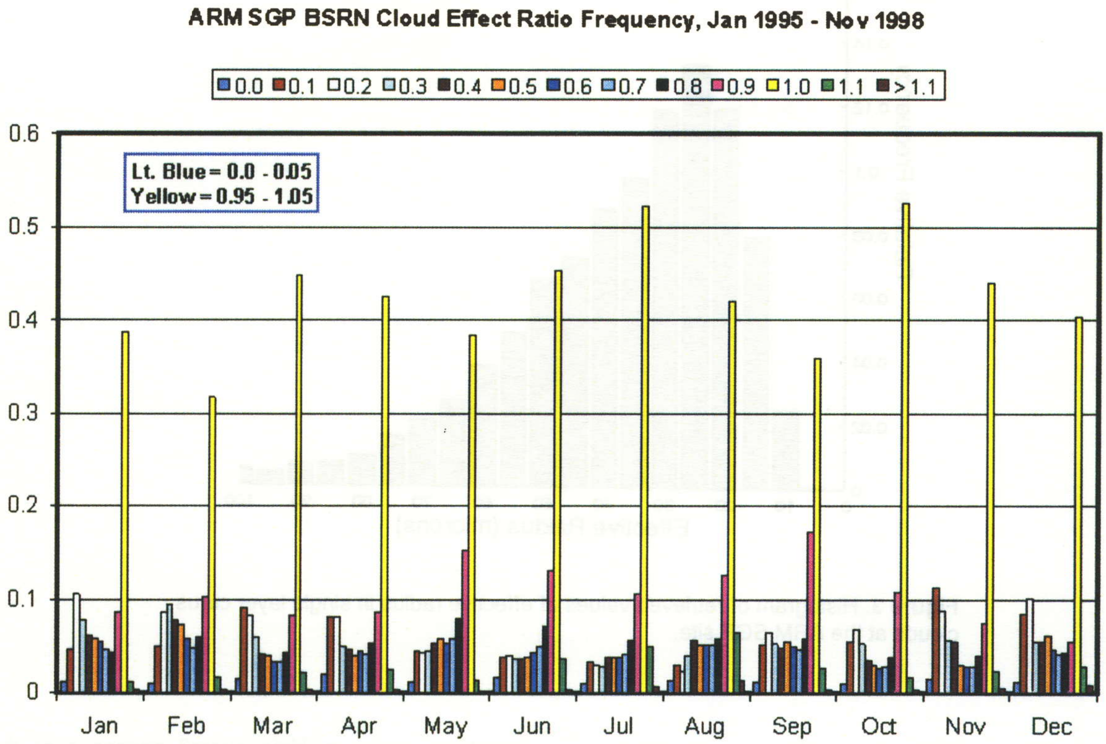

Figure 2. Monthly Histograms of the Cloud Effect Ratio. Histograms have a width of 0.1 and values are centered at 0.1, 0.2.

The increase in cloud effect ratios greater than 1 during the warmer months can also be traced to the occurrence of deep convection.

Cloud Microphysics. Combining information from active and passive remote sensors allows us to derive important information about the internal structure of clouds that previously was largely obtainable only by aircraft penetration. A straightforward example of this approach is shown in Figure 3, based on work by Mace et al. (2000).

For these retrievals we use the integrated radar reflectivity from a cirrus layer combined with the nadir emission in the thermal window measured by a vertically staring emission interferometer. The emission from a cirrus layer is largely a function of the total ice mass, while the integrated reflectivity is a strong function of particle size. The combination of the two measurements into a single algorithm allows us to deduce both quantities. The histogram of effective particle radius is based on data from single-layer cirrus only and is comprised of hundreds of events. The most probable value is around 25 to 30 microns, but the distribution has a significant tail of larger values. Similar histograms can be derived for other properties and other cloud types.

3. SATELLITE VALIDATION STRATEGY

The typical approach to validation of satellite cloud property retrievals over the past several decades has been to use aircraft to sample underneath the satellite ground track using one of two approaches. In one approach, the aircraft is flown well above the cloud carrying an instrument matched to the satellite instrument. The same retrieval algorithm is applied to both instrument streams and compared. In the second approach, the aircraft is flown in the cloud to make direct measurements of the property being retrieved. Both of these approaches suffer from several common problems. Aircraft are expensive to operate so flight hours are limited. Weather in general and clouds in particular are highly variable so obtaining

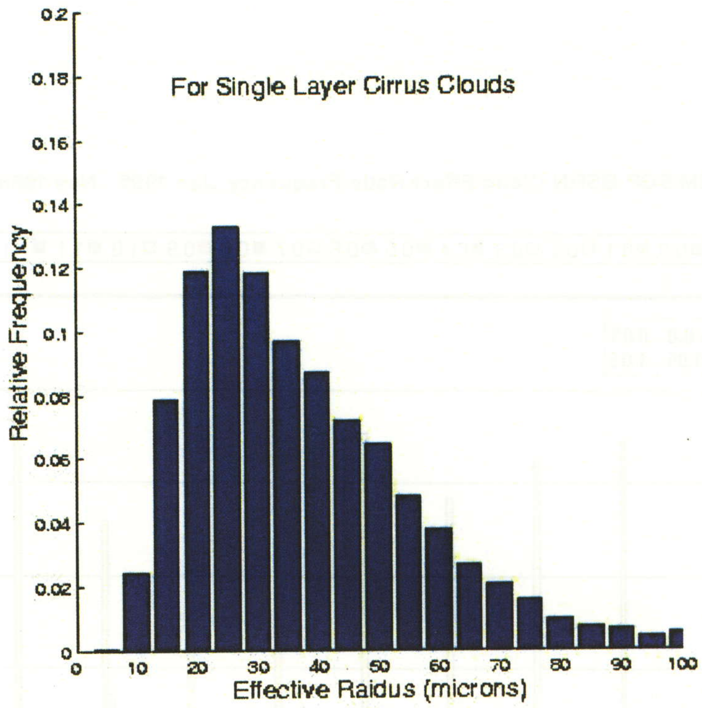

Figure 3. Histogram of retrieved values of effective radius in single layer cirrus clouds at the ARM SGP site.

the requisite conditions (e.g., single layer cirrus clouds) underneath the satellite ground track can take considerable time and effort. The footprint of the satellite is much larger than that of the aircraft, particularly for in situ observations, making matches difficult unless clouds are extensive and relatively homogeneous. The result is that the validation of the satellite properties is limited to a handful of points often with large uncertainties attached to them.

The advent of continuously operating ground-based instruments presents an opportunity to employ a significantly different approach to this problem. Because the ground-based sites can deploy a greater variety of instruments, including active sensors, than can be deployed from satellites, ground-based retrievals of cloud properties are more constrained and hence likely to be more robust and more accurate. In situ measurements over the ground sensors are easier to acquire because matching a satellite orbit is no longer part of the problem. Waiting for the right weather conditions is still an issue but when those conditions occur, multiple aircraft passes over the ground sensors are possible leading to a better validation set. The suite of ground-based instruments also lends itself to validation by consistency of measurements. For instance, in the case of the cirrus retrievals shown in Figure 3, we validate the result in part by looking at whether the retrieved ice column mass and particle size can be used to compute the observed solar irradiance at the surface.

Combining in situ validation with consistency checks at the site allows us to develop confidence in our ground-based retrievals of cloud properties. The continuous instrument operations at the sites enables the creation of frequency distributions of retrieved properties. These together provide the basis for a new and better strategy for the validation of cloud properties. Each satellite retrieval of cloud properties that occurs in the vicinity of a ground-based site is compared to a simultaneous retrieval from the ground-based site. For some satellite instruments and some sites, many coincident samples will occur.

For other pairs, relatively infrequent coincident sampling will occur. In either case, over the lifetime of the satellite, we can expect to develop a statistically significant data set of coincident samples that will allow us to determine how well the satellite retrievals agree with the ground-based retrievals. Given that we have established the level of confidence in the ground-based retrievals, this will allow us to attach confidence levels to the satellite retrievals. Furthermore, we can define an area of interest around the site where we think that cloud properties should be essentially similar. We can take all the satellite retrievals within this geometric area and compare them to the temporal distribution achieved at the ground site. Differences in the two distributions will then reflect to a large extent the differences between the retrieval techniques. For example, if we are interested in a distribution of cirrus optical depth, we may find that the satellite distribution fails to have the same small optical depth tail that we find from the ground. This may well be due to the fact that the satellite radiometric measurements have less sensitivity to thin cirrus than does ground-based lidar. Such information can be used to calibrate satellite distributions.

Considering specifically space-born radar, it is quite clear that ground-based radars such as the MMCR will be a vital component of the validation strategy. These radars will provide higher resolution and more sensitive detection of cloud layers. Comparing the ground-based results to the satellite results will allow us to determine the extent to which clouds can be sampled from space and the amount of cloud not sampled from space due to the limitations of the cloud based radar.

4. REFERENCES

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