14A.1 **Use of Radar Profilers as Tools for the Determination of Space-Time Variability of Precipitation Parameters**

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1. INTRODUCTION

For remote sensing of precipitation from radar and satellites to fulfill its ultimate potential it will be necessary to improve the precision of rain retrievals and to optimize the assimilation of the data into numerical models. It is well known from developments in data assimilation that for optimal performance models require information on the error covariance of the parameter being measured. In general, this means information is required on the measurement error of instruments as well as the representativeness of the measurements themselves. In the case of precipitation measurement it is necessary to develop more information on the variability of precipitation fields within precipitating cloud systems. This paper considers approaches to the determination of space time variability of precipitating cloud systems using profilers and scanning radars.

During the past decade Doppler radar profilers that operate near 1 GHz and 3 GHz have been developed at the NOAA Aeronomy Laboratory for use in dynamics and precipitation research (Carter et al., 1995; Ecklund et al., 1999). The profilers have been used extensively in numerous field campaigns during the past decade. The field campaigns include the Coupled Ocean Atmosphere Response Experiment (COARE) that took place in the western Pacific warm pool region during 1992-93, and the Tropical Rainfall Measuring Mission (TRMM) Ground Validation Field Campaigns: TEFLUN (Texas and Florida; 1998), TRMM LBA (Brazil, January –February 1999) and KWAJEX (August–September 1999). For a sample of profiler observations from the TRMM Field Campaigns see Gage et al. (2002).

Profiler observations yield time height cross-sections of equivalent reflectivity, Doppler velocity and spectral width that illustrate the evolution of precipitating clouds systems. In the presence of precipitating clouds backscattering from hydrometeors is dominant and the Doppler velocity provides a measure of the fall velocity of hydrometeors. The vertical structure of these parameters has been used to classify the precipitating cloud systems into several different categories. These observations document the prevalence of deep anvil cloud systems over the Pacific warm pool region. They also show the relative abundance of rainfall from stratiform and convective components of precipitating cloud systems and the continuous observations reveal the diurnal evolution of the precipitating clouds over the profiler.

2. VARIABILITY OF PRECIPITATION FIELDS AND ASSIMILATION OF PRECIPITATION DATA INTO MODELS

The assimilation of data into numerical forecast models is now a mature science with established methods for optimally assimilating data using several variational techniques (Daley, 1997). Inherent in the established methodology for data assimilation is the need to specify model error and observational error. The observational error contains a component due to instrument uncertainty and a component due to the variability of the fields being sampled. In most cases meteorological fields are imperfectly sampled and the observational error is dominated by the natural variability.

A few studies have been conducted assimilating radar observations into models. Grecu and Krajewski (2000, 2001) report simulation studies that investigate the effect of assimilation of radar data on rain forecasting. Sun and Crook (1997) report on retrieval errors in the assimilation of radar data in a numerical model. Several studies have shown the advantages accrued from utilizing remote sensing observations in numerical models. Satellite retrievals of precipitation have been utilized in model studies by Hou et al. (2001) and Krishnamurti et al. (2000).

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2.1 Space-time Variability and Measurement Uncertainty

Studies of variability of meteorological quantities such as rain rate often show a scale dependence that makes it problematic to compare observations that are made by instruments that are sensitive to different scales (Crane, 1990; Lovejoy and Schertzer, 1990; Over and Gupta,1990). This is an issue of paramount importance for both radar and satellite estimates of precipitation. As pointed out by Ciach and Krajewski (1999), in the context of rainfall estimation utilizing radar and rain gauges, no direct comparison is possible because of the large difference in areas sampled by these instruments. Radar grid cells used for rain mapping are typically of the order of 1-10 km^2 while rain gauges typically sample an area of 100 cm^2. Because of the scale dependence of precipitation fields, the natural variability of the rain fields will dominate the measurement uncertainty. In order to overcome this problem Ciach and Krajewski (1999) develop an approach called the error separation method (ESM) for partitioning the radar minus rain gauge difference variance into a rain rate estimation error variance and the rain gauge sampling error variance. The rain gauge sampling error variance accounts for the lack of representativeness of a point measurement by the rain gauge.

2.2 Error Covariance for Data Assimilation

The importance of the specification of error covariance of a quantity being assimilated into a model is made clear by Daley (1997). This point is also emphasized by Keeler and Ellis (2000) who discuss the determination of the error covariance matrix for radar data assimilation purposes. This topic is also considered by Sun and Crook (1999) who state the observational component of the cost function in the form

$$J_{obs} = \sum[Hx_k - y_k]^T O^{-1} [Hx_k - y_k] \qquad (1)$$

where J_{obs} represents the departure of the numerical model variables from the related radar observations. As explained by Keeler and Ellis, x_k is the model state vector, and y_k is the radar observation vector, H is the observation operator and O is the observation error covariance matrix.

The error covariance matrix is further decomposed into the instrument error O_i^{-1} and a representativeness error O_r^{-1}. The instrumentation error is the familiar precision or statistical error of making the measurement of the mean value of a fluctuating quantity and the representativeness error refers to the natural variability of the quantity that is being measured.

3. USE OF PROFILERS FOR THE DETERMINATION OF SPACE TIME VARIABILITY OF PRECIPITATION PARAMETERS

3.1 Retrieval of Precipitation Parameters Using Profilers

Over the past two decades, methodologies have been developed to retrieve the raindrop size distribution as a function of altitude using the Doppler velocity spectra observed by vertically pointing profilers (Hauser and Amayenc, 1981; Wakasugi et al., 1986; Schafer et al., 2002). These profiler-retrieved drop size distributions (DSD) are estimated at each range gate and can be expressed mathematically as the number concentration, *N(D)*, using the modified gamma functional form described by Ulbrich (1983)

$$N(D) = N_0 D^{\mu} \exp\left[-\Lambda D\right] \qquad (2)$$

where N_o, μ, and Λ are the scale, shape, and slope parameters, respectively. The methodology for estimating the DSD from a single profiler is described in detail in Williams (2002). From the DSD, the different parameters of the precipitating cloud can be calculated at each range gate and include:

Median Diameter, D_o:

$$\int_0^{D_o} N(D) D^3 dD = \int_{D_o}^{\infty} N(D) D^3 dD \qquad (3)$$

Mean Diameter, D_m:

$$D_m = \frac{\int_0^{\infty} N(D) D^4 dD}{\int_0^{\infty} N(D) D^3 dD} \qquad (4)$$

Liquid Water Content, LWC, g /m^3:

$$LWC = 10^6 \frac{\pi}{6} \int_0^{\infty} N(D) D^3 dD \qquad (5)$$

Rain Rate, R, mm hr^{-1}:

$$R = 6x10^3 \pi \int_0^{\infty} N(D) v(D) D^3 dD \qquad (6)$$

with N(D) and D in the units of cm^{-4} and cm, respectively.

The profiler retrieved DSDs were estimated for the 17 September 1998 rain event that passed over the profiler. Figure 1 shows the profiler retrieved number concentrations at 327 meters above the ground and the DSDs estimated by the surface Joss-Waldvogel

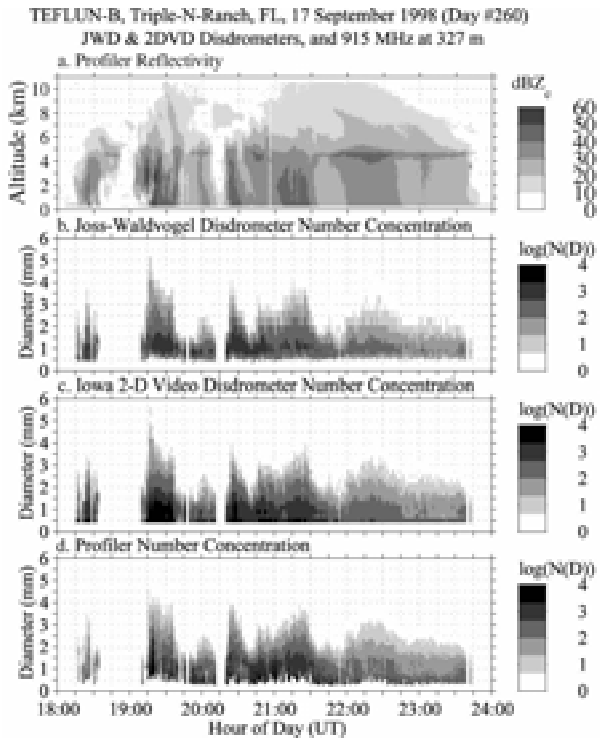

Figure 1. a) Equivalent reflectivity, associated with a mesoscale convective system passing over the profiler at the Triple N Ranch during TEFLUN B. Number concentrations observed by b) JWD, c) 2DVD and c) retrieved from profiler during the passafe of this convective system.

Disdrometer (JWD) and 2-dimensional Video Disdrometer (2DVD) operated by the University of Iowa. All three instruments resolve the maximum diameter for each minute observation which agree very well. The maximum resolved diameter of 5.25 mm for the JWD (due to hardware constraints) is reached during the convective rain near 19:15 UTC. In contrast to the similarity in resolved maximum diameter by all three instruments, discrepancies exist in the small diameter regime. The JWD appears to be underestimating the number of small drops relative to the other two instruments. The underestimation occurs throughout the event. These similarities and differences between the three instruments are described in more detail in Williams et al. (2000).

3.2 Required Measurements

To determine the natural variability of a meteorological quantity, such as a precipitation parameter or rain accumulation, it is necessary to take many measurements in a region. Continuous measurements can help but it is important to be able to assess the horizontal and vertical structure of the measured quantity. Ciach and Krajewski (1999) outline an approach to the estimation of error variance as it might apply to the area of a satellite observation pixel. The measurements that are needed fall within the subgrid scale of the satellite pixel. For example, given a 5 km x 5 km satellite observing area the domain should be measured with instruments capable of observing at a small fraction of the satellite pixel. Such observations should be distributed within the satellite observation area.

A network of paired rain gauges can be used to determine the structure of the surface rain fields within the radar observation pixel. This can be done by determining the correlation function from gauges separated spatially by varying amounts as explained in Ciach and Krajewski (1999). Profilers can be used to bridge the scales between satellite, radar and rain gauge measurements. At an altitude of a few hundred meters, the typical area of a profiler measurement is about 10^3 m^2 which is intermediate in scale between the rain gauge and the radar or satellite observation pixel size. A distributed array of profilers can then be used to determine the correlation structure at any altitude within the rainfelds being measured so that the vertical structure of the precipitation parameters and their horizontal variability can be determined.

A wind profiler (as opposed to a precipitation profiler) would help link the spatial and temporal structure of the precipitation fields. As is the case for turbulence it is anticipated that the Taylor transformation may be a satisfactory way to relate spatial and temporal variability. The Taylor transformation simply relates time scales and space scales by means of the advection velocity which is equal in most cases to the mean wind velocity which can be measured by the profiler. Since profilers measure nearly continuously in time it should be possible to test whether the Taylor transformation is a valid means to relate temporal and spatial variability on these scales. If the Taylor transformation can be used with confidence at these scales, it may be possible to utilize a single profiler to determine correlation structure in future campaigns.

4. CONCLUDING REMARKS

In this paper we have reviewed the literature on mesoscale variability of precipitating cloud systems as it applies to the specification of the representativeness of observations of precipitation parameters retrieved from radar profilers and other remote sensing instruments. It is well known that the optimal use of these observations in numerical models requires specification of error covariance of the fields to be assimilated in the models. Profilers in combination with other ground based instruments are well suited for the measurements required to specify the error covariance needed for the models. It is recommended that efforts be made to obtain these measurements to facilitate the assimilation of remote sensing observations into models.

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