Ground Based Rainfall Measurements at the NASA Wallops Flight Facility

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ABSTRACT

The rainfall measurements collected at the NASA Wallops Flight Facility during the first 4 months of 2001 were analyzed to study the small-scale variability of rainfall and to evaluate the instruments performance with respect to each other. The instrument platform included impact and optical type disdrometers, tipping bucket rain gauges, and sonic anemometers. An X-band polarametric (X-POL) radar that was situated approximately 3.8 km from the disdrometer site was also operated for two months period starting from February 20, 2001. The disdrometers helped to calibrate the X-POL radar.

Winds played a crucial role on the performance of both rain gauges and disdrometers. In the presence of strong winds, disdrometers, particularly 2-dimensional video disdrometer (2DVD), severely underestimated the rainfall. The underestimation of rainfall by impact disdrometers was due to sampling errors of the drops larger than 5.0 to 5.5 mm in diameter. The drops less than 2 mm in diameter were also undersampled due to disdrometer dead time and background noise generated by the winds. The design of the 2DVD was problematic to collect the drop samples falling at an angle from the vertical axis. The rain amounts between the same types of disdrometers and of rain gauges were also varied as a function of wind speed. The variations in drop size distribution measured within a radar pixel of 2 x 2 km resulted in 1 to 1.7 dB difference in reflectivities. This should be considered a source of error in radar rainfall estimates. It was shown that the horizontal reflectivity was insensitive to variations in drop shape while observed axis ratios resulted in lower differential reflectivity than equilibrium axis ratios. The X-POL radar measurements of horizontal reflectivity was in good agreement with the reflectivity calculated by the disdrometer while the radar differential reflectivities were consistently lower than the disdrometer differential reflectivites.

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1. Introduction

Precipitation is one of the key components of the unending circulation of water within our atmosphere, known as the *hydrological cycle*. As shown in Figure 1, the sun's energy evaporates the water, winds carry the water vapor elsewhere, and the water vapor condenses back to its liquid form (cloud formation) and then may precipitate out of the cloud. Precipitation over the oceans is greater than that over land surfaces. Nevertheless, evaporation over the oceans exceeds precipitation while vice versa is true over land. The surface water balance can then be defined as (averaged over a long period of time and neglecting dewfall):

$$\Delta f = P - E \qquad (1)$$

where P is the precipitation by rain or snow, E is the evapotranspiration, and Δf is the runoff. The latitudinal distribution of the variables in (1) are shown in Figure 2. Precipitation peaks near the equator, with a secondary maximum in the middle latitudes of both hemispheres. The convection along the intertropical convergence zone (ITCZ) is mainly responsible for producing the heavy precipitation in equatorial regions while the secondary maximum is associated with mid-latitude weather systems. The evaporation exceeds precipitation over the sub-tropics where the runoff is negative (Figure 2).

Over the land, 75 cm of precipitation falls in a year (Figure 1). This corresponds to an energy release of about 54 W m^{-2}. Over the ocean, precipitation (107 cm yr^{-1}) produces an energy release of about 77 W m^{-2}. This energy release, known as *latent heat*, mainly balances the net radiative cooling of the atmosphere. Therefore, precipitation is a key component of the atmospheric energy budget, which in turn plays an important role in the general circulation of the atmosphere. The time rate of change of the energy content of an atmospheric column of unit horizontal area extending from the surface to the top of the atmosphere is balanced by the combined effects of net radiative heating of the atmospheric column, sensible heat transfer from the surface to the atmosphere, the horizontal divergence of energy out of the column by transport in the atmosphere, and the heating of the atmospheric column by latent heat release during precipitation. The latitudinal distribution of these components averaged over longitude and over the annual cycle is shown in Figure 3 (Hartmann 1994).

About 2/3 of the global precipitation falls in the tropics and the tropics contain 70% of the world's oceans. 75% of the energy that drives the atmospheric wind circulation comes from the latent heat released by tropical precipitation. Therefore, there is a great interest to measure the rainfall in the tropics. Precipitation is one of the most difficult atmospheric parameters to measure due to large variations in space and time. It requires continuous monitoring at a scale that can be resolved by cloud models.

The Tropical Rainfall Measuring Mission (TRMM) is dedicated to measuring tropical and subtropical rainfall through microwave, visible, and infrared sensors and the "first space borne" radar. TRMM is a joint project between the United States (NASA Goddard Space Flight Center) and Japan (National Space Development Agency of Japan). The main objectives of TRMM include obtaining and studying data sets of tropical and subtropical rainfall measurements and understanding how interactions between the sea, air, and land masses produce changes in global rainfall and climate. Also, TRMM will help improve modeling of tropical rainfall processes and their influence on global circulation in order to predict rainfall and variability at various time scale intervals. The TRMM mission will also provide an opportunity to test, evaluate, and improve the performance of satellite rainfall estimate measurements and techniques for the upcoming Global Precipitation Measurement (GPM).

The TRMM satellite was launched in November 1997 with a life expectancy of 3 years. One of the major accomplishments of the TRMM mission was producing a three-year climatology of tropical rainfall by reducing the rainfall measurement uncertainty from 50% to 25%. Inter- and intra-seasonal variations of tropical rainfall were also studied through TRMM observations. Interestingly, the first year of the mission (1998) was coincidently an El Niño year, which was characterized by warm sea surface temperatures and substantial differences in regional inter-seasonal rainfall. The TRMM satellite is still in orbit. At the time of this report, the altitude of the satellite is about raised from 350 km to 400 km. This would extend its life expectancy to March 2003 or beyond.

The sampling time of the TRMM satellite is about 28 hours. The satellite image can be considered a snapshot of a developing, mature, or decaying tropical system. To study the life cycle of a tropical convection, more frequent sampling is needed. Hydrological applications also require frequent sampling of a precipitating weather system. The upcoming GPM mission will be able to sample, at a given location, every 3 hours with its core satellite and constellation satellites. The GPM is designed to have a 65° inclination angle, which will make it possible to study mid-latitude weather systems. One of the key objectives of GPM is to decrease the uncertainty of the rainfall fall measurements to 10%.

To evaluate the TRMM satellite rainfall products, surface rainfall are closely monitored at selected sites that represent tropical rainfall worldwide. For instance, the NASA TRMM office operates four direct validation sites representing oceanic, coastal, and continental rainfall. These validation sites include a dense rain gauge network, and scanning Doppler radar. It should be also noted that ground validation efforts have also been conducted by other government agencies and universities in the United States and selected countries including Japan, United Kingdom, France, and Israel. For instance, the United Kingdom established a ground validation site in Singapore where rain gauges, a disdrometer, and scanning Doppler radar are being operated. In addition to the continuous observations at selected sites, several field campaigns were conducted by NASA and NASDA to further investigate microphysical processes of precipitation and to provide a better data source to improve performance of the satellite rainfall algorithms.

Following field campaigns, a ground-based instrumentation test site was established at the NASA Wallops Flight Facility. One of the key purposes of this test site is to provide long-term observations of drop size distributions through disdrometer measurements. The disdrometers were part of the two month long TRMM field campaigns, but they were not operated at any of the direct data acquisition sites mentioned above. The new site allows studying small-scale variability of drop size distribution as well as the disdrometer’s accuracy to measure drop size distribution and related integral parameters.

The main goal of this study is to analyze the rainfall measurements collected at the NASA Wallops Flight Facility. The data used in this study was collected between January and April 2001. In section 2, we will describe the instruments used to gather the data for the experiment. Section 3 will analyze four months of data for the purpose of determining rain accumulation statistics. Section 4 will comprise of the results of two case studies. We will offer a summary and conclusions in Section 5.

2. Instrumentation

The Wallops Island Data Acquisition Network consists of various types of disdrometers and rain gauges. The network includes six instrument sites nearly aligned between the transmitter and receiver towers of the microwave link (Figure 4). Each site has a tipping bucket rain gauge, four of which equipped with optical rain gauge and three of which with Joss-Waldvogel disdrometers (JWD). One of the sites, also known as the master site, includes two more tipping bucket rain gauges, another JWD, a two dimensional video disdrometer (2DVD), 2 sonic anemometers, and an X-band disdrometer (Pludix) as shown in Figure 5. For a two-month period, starting from February 20, 2001, an X-band polarametric radar (X-POL) was also operated. It should be noted that all four JWDs were at the master site prior to March 20, 2001. In this section, we will briefly describe the main characteristics of JWD, 2DVD, tipping bucket rain gauge, sonic anemometer, and X-POL radar.

a. Joss-Waldvogel Disdrometer (JWD)

The JWD was originally designed for the purpose of calculating radar reflectivity. It is an impact disdrometer, which measures the drops size by the impact of the drop. The JWD has a sampling cross section of 50 cm^2, and drops are sorted into 20 size intervals ranging from 0.3 mm to about 5.0 mm to 5.5 mm. The boundaries of the 20 channels are not uniform, and increase with drop size from 0.1 mm to about 0.5 mm. Each unit has a different calibration and therefore has different channel boundaries. At the Wallops Flight Facility, output from the JWD was averaged for 1-minute intervals. If the JWD recorded less than 10 drops or rain rate is less than 0.1 mm hr^{-1} in a one-minute time interval, then that minute was disregarded. The rain rate can be directly calculated as:

$$R\,(\text{mm hr}^{-1}) = \frac{6\ \ 10^{-4}\pi \sum_{i=1}^{20} C_i D_i^3}{A\Delta t} \qquad (2)$$

where C_i is the number of drops in the i*th* channel, D_i is the middle size of the i*th* channel in mm, A is the sampling cross section in m^2, and Δt is the sampling time in seconds. The other integral parameters require an assumption of terminal fall speed of the drops. For example, concentration is calculated as follows:

$$N(\text{m}^{-3}) = \frac{\sum_{i=1}^{20} \frac{C_i}{v_{T_i}}}{A\Delta t} \qquad (3)$$

where v_T is the terminal fall speed in m s^{-1}. The Gunn and Kinzer (1949) observations of terminal fall speed were adopted for this study. The liquid water content is another important parameter and is used for cloud modeling studies and is related to the third moment of drop size as follows:

$$M(\text{g m}^{-3}) = \rho_W\ \ 10^{-3}\ \ \frac{\frac{\pi}{6}\sum_{i=1}^{20} \frac{C_i D_i^3}{v_{T_i}}}{A\Delta t} \qquad (4)$$

where ρ_W is the density of water in g cm^{-3}. The reflectivity in the Rayleigh scattering regime is related to the sixth moment of the drop diameter as follows (Tokay et al. 2001a):

$$Z(\text{dB}) = 10\log_{10} \frac{\sum_{i=1}^{20} \frac{C_i D_i^6}{v_{T_i}}}{A\Delta t} \qquad (5)$$

The horizontal reflectivity (Z_H) can be calculated by multiplying (5) by a dimensionless shape factor (S_H). The shape factor is a function of the reflective index of water and drop shape. The drop shapes used in this study were adopted from the mean axis ratios offered by Andsager et al. (1999) and equilibrium axis ratios of Beard and Chuang (1987). Differential reflectivity (ZDR) is the ratio of horizontal and vertical reflectivity given by:

$$ZDR = 10\log_{10}\left(\frac{Z_H}{Z_V}\right) \qquad (6)$$

Like Z_H, vertical reflectivity (Z_V) is a function of drop shape and refractive index of water.

The JWD has its own shortcomings. It tends to underestimate the number of small drops in heavy rain due to ringing of the styrofoam cone when it is hit by the drops, known as the *disdrometer's dead time*. A correction matrix is provided by the manufacturer, but is prone to error in the drop size intervals in which no drops exist. Therefore, it is not used for this study. The JWD also assumes that the raindrops fall at their respective terminal velocity. If updrafts and downdrafts are present in the vicinity of the JWD, then the fall speed of the drop will change compared to the given value. It also cannot resolve drops larger than 5.0 mm to 5.5 mm.

b. 2-Dimensional Video Disdrometer (2DVD)

2DVD is an optical disdrometer that measures not only drop size but also drop fall speed and shape. The instrument consists of an outdoor sensor and electronics unit, and an indoor-use computer terminal. The image of the falling drop is scanned twice in two planes separated by about 6 mm. The separation between the two planes and time delay are used to determine the fall speed of the drops. An algorithm is then applied to the two planes to determine drop shape and the volume from which the equivalent diameter can be determined. The 2DVD has a sampling area of 100 cm^2 (twice that of the JWD) and is calibrated by dropping metal balls of known size into the orifice.

The 2DVD occasionally records random small drops due to the splashing of drops on the side of the disdrometer. Also, it under samples the number of drops in windy conditions. This will be shown in section 4c. The turbulence and wind sheer created by the instrument can also underestimate or overestimate the number of drops (Nespor et al.

2000). The drops beyond ±50% of their terminal fall speed are excluded from the analysis. This excludes about 15 to 20% of the drops, mainly less than 2 mm in diameter. The integral rainfall parameters are then calculated using (2) through (6), except that measured fall speed and sample area of the individual drops are employed.

c. Tipping Bucket Rain Gauge

The tipping bucket rain gauge is a reliable sensor used to measure rainfall volume. Rain enters the gauge through an orifice 20 cm in diameter (made by Qualimetrics) and fills one of two buckets located inside the gauge. A mesh screen is used for the purpose of keeping insects out. Each tip represents 0.01 inches (0.254 mm) of rainfall. As the bucket tips, a reed switch makes a momentary closure (approximately 100 ms) that is used to trigger a logging device to record the measurement. The measured water drains out the bottom of the instrument.

The cylindrical gauge is about 46 cm high and typically situated on the top of a wooden box or pole to prevent flooding. Ideally, the gauge should be buried in the ground (pit gauge) so that it will not be affected by winds and turbulence. Since the instrument records number of tips in a few seconds, it does not provide precise rain rate, especially in light rain. Also, the duration of rain events as well as the beginning and ending may not precisely be known from the time of the tip. An optical rain gauge and/or disdrometer may be operated next to the tipping bucket rain gauge to determine precise rain rate and rain duration.

d. X-Band Polarametric Radar (X-POL)

Doppler radars used for operational purposes by the National Weather Service are capable of determining return power (i.e. reflectivity) and the velocity in the radial direction (Rinehart 1991). The X-POL, on the other hand, is used for research purposes and is capable of measuring polarametric parameters, horizontal reflectivity, differential reflectivity, differential phase, and the cross correlation between horizontal and vertical polarization. X-POL has much less ground clutter than the Doppler radar, whereas it has a more significant attenuation problem. Depending on the rainfall rate, the signal typically attenuates at around 40 km.

Basic characteristics of the radar are listed in Table 1. The beam width of the X-POL radar was 0.9°. The radar scanning strategy was designed such that 1-minute surveillance scan followed by 9 minutes of range height indicator (RHI) scan and 50 minutes of sector scan. The sector scan was between 55 to 155° and at elevations 1.8 and 2.7°. The master site was at 144° azimuth and 3.825 km from the radar. Not counting the curvature of the earth, the height of the scanned area above the disdrometer site turned out to be 113 m for the first elevation angle. The master site was sampled every 45 seconds during sector scan at an elevation 1.8°. (Marner et al. 2001)

e. Sonic Anemometer

The sonic anemometer is used to measure wind speed in 3 dimensions and wind direction. It has a measurement range of ±20 m s^{-1}. It was an accuracy of about ± 0.05 m s^{-1} and a resolution of 0.01 m s^{-1}. The wind direction has an accuracy of ±0.1° and a resolution of 0.1°.

3. Rainfall Accumulation Statistics

The rain total of each rain event was calculated for each rain gauge and disdrometer. The comparison of rain totals between gauges, between disdrometers, and between gauges and disdrometers provided an insight on the performance of each instrument as well as natural variability of rainfall. A rain event is defined based on one rainy minute in 15 consecutive minutes. If the rain accumulation is less than 1 mm, then that rain event is not included in the analysis. Rain gauge totals are assumed to be truth when determining the accuracy of disdrometers. Therefore, the rain gauge totals are first compared with respect to each other. The mean rainfall is calculated as:

$$\overline{\mathrm{RG}} = \frac{1}{N}\sum_{i=1}^{N}\langle \mathrm{RG_i}\rangle \qquad (7)$$

where

$$\langle \mathrm{RG_i}\rangle = \frac{\mathrm{RG_i1} - \mathrm{RG_i2}}{(\mathrm{RG_i1} + \mathrm{RG_i2})/2} \qquad (8)$$

and the standard deviation is calculated as:

$$\mathrm{SD_{RG}} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\langle \mathrm{RG_i}\rangle - \overline{\mathrm{RG}}\right)^2} \qquad (9)$$

where N is the number of rain events and RG_i1 and RG_i2 are the rain accumulations for two different rain gauges in mm. It should be noted that each rain event was equally weighted in the statistics. The percentage bias between gauges and disdrometers is also useful to determine the instrument's performance.

Figure 6a presents the comparison of first rain gauge (RG1) and second rain gauge (RG2). A very good agreement between these two gauges is evident from the statistics of low mean and standard deviation of rain totals. The third rain gauge (RG3), on the other hand, had lower readings such that RG1 and RG2 were 12 and 10% higher in the mean, respectively. This is perhaps due to the natural variability of rainfall since RG3 is located 11 m from RG1 and 8 m from RG2 while RG1 is located only 3.5 m from RG2. The instrument error may also contribute to the low readings of RG3.

For comparing two disdrometers with each other, the rainfall statistics were calculated similar to (7) – (9) except RG1 is JWD1 and RG2 is JWD3. Prior to March 21, 2001, all four JWDs were nearby to each other resulting in 4 – 8% differences in mean rain totals with 10 – 12% in standard deviation (Figure 6b). Starting March 21, 2001, the second and fourth JWDs (JWD2 and JWD4) were placed 650 m and 1.7 km from the master site, respectively (Figure 4). JWD2 had 5% higher accumulation than JWD1 on average with 21% in standard deviation while JWD4 had 11% lower accumulation on average than JWD1 with 15% standard deviation. These relatively higher means and standard deviations are indicative of the natural variability of rainfall.

The rainfall statistics presented in Figures 6c and 6d follows (10) – (12) where rain gauge measurement is considered to be truth. The mean percentage error of a disdrometer is calculated as:

$$\overline{\mathrm{DIS}} = \frac{1}{N}\sum_{i=1}^{N}\langle \mathrm{D_i} \rangle \qquad (10)$$

where

$$\langle \mathrm{D_i} \rangle = \frac{\mathrm{RG_i} - \mathrm{DIS_i}}{\mathrm{RG_i}} \qquad (11)$$

DIS_i represents measurements of either JWD or a 2DVD. The standard deviation was then calculated using:

$$\mathrm{SD_{DIS}} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\langle \mathrm{D_i} \rangle - \overline{\mathrm{DIS}}\right)^2} \qquad (12)$$

The JWD underestimates the rainfall most of the rain events (60%) with respect to RG1 as shown in Figure 6c. The same is true when JWD1 is compared to the RG2, but it was not the case with respect to RG3. This is due to the low readings of RG3. These statistics were based on limited number of rain events. The longer observation period is required to distinguish the natural variability of rainfall versus from the instrumental errors. The 2DVD also underestimated the rainfall except for a few rain events (26% of the time). In the presence of strong winds, 2DVD significantly underestimates the concentration of drops. These events were noticeable as 2DVD rain totals were much less than gauge rain totals. This finding is further investigated in the following sections.

4. Case Studies

Two rainfall events were studied to examine the variations in the characteristics of drop size distribution and integral rainfall parameters. Both rain events migrated from the east and southeast indicating maritime characteristics of the precipitation. The main differences between the two rain events is that the first rain event occurred on March 21, 2001 had stronger winds than the later event occurred April 11, 2001. Here, the characteristics of rainfall and of drop size distribution are shown for these two rain events utilizing impact and optical disdrometers, rain gauges, sonic anemometer, and X-POL radar.

a. Rainfall Time Series

Figure 7 shows rainfall time series derived from JWD1, JWD4, and 2DVD for the two rain events mentioned above. Wind speed time series including mean and standard deviation are also given.

Although rain started nearly after midnight in the first rain event, rain intensity was very light (mostly < 1 mm hr^{-1}), and therefore excluded until 6:40 LT. It should be reminded that JWD1 and 2DVD were about 8.5 m apart from each other (Figure 5) whereas JWD4 was about 1.7 km from JWD1 (Figure 4). The rain totals were substantially different between impact and optical disdrometers as well as between disdrometers and rain gauges. The rain gauge rain totals were near 60 mm, 2.4 times of the rain total of the 2DVD and 1.6 times of the rain total of JWD. The windy conditions, particularly during heavy rainfall, were the main cause of the underestimation of the rainfall by the 2DVD. For instance, during heavy rainfall (10:24 – 10:42 LT), mean wind speed were about 7 m s^{-1}. The underestimation of rain totals by JWD was partly due to underestimation of small drops (D < 1 mm) in heavy rain and partly due to the lack of very large drops (D > 5 mm). The trend of local maxima of JWD4 occurred prior to that of JWD1, consistent with the storm direction. The rain totals of the JWD at the three different locations also showed substantial variations such that JWD2 recorded 51 mm or rainfall, which was 36 and 27% higher than JWD1 and JWD4, respectively.

The second rain event should be considered a combination of two rain events since there was more than a 15-minute gap within the rainfall time series (Figure 7b). The winds were relatively weak for the entire rain event. In particular, it was 3.2 m s^{-1} during heavy rainfall (12:11 –12:40 LT). Unlike the previous event, the 2DVD had higher rain totals than the JWD. An excellent agreement was evident between rain gauges and 2DVD rain totals. Compared to the previous rain event, the local maxima of JWD1 were before the local maxima of JWD4. JWD4 received 2 mm of rainfall less than JWD1 as the peak rainfall of JWD4 was 18.0 mm hr^{-1}, 44% that of JWD1 thereby affecting the total rainfall accumulation.

b. Drop Size Distributions

Drop size distribution (DSD) is essential in understanding the physics of precipitation processes; therefore it plays a key role in remote sensing (i.e. radar) estimation of rainfall. If the DSD was known within measured radar volume, the surface rainfall could be estimated by incorporating microphysical processes between the altitude of the radar measurement and the surface. In reality, radar measures the return power (i.e. reflectivity) from falling hydrometeors, which is proportional to the sixth moment of the drop size. The rain rate, on the other hand, is proportional to the third to fourth moment of the drop size. A nonlinear relationship between measured reflectivity and estimated rain rate ($R=AZ^b$) relies on the knowledge of the DSD.

Consider a single drop of 5 mm in 1 m^3 of radar volume. The measured reflectivity would be 42 dB. If the radar volume consists of 1 mm drops, then 15,625 drops would be required to have the same reflectivity. The rain rate calculated for the first scenario above would be 2 mm hr^{-1}, while for the second scenario, the rain rate is 118 mm hr^{-1}. If one considers two DSDs, at the same rain rate, the one that has more large drops and less small drops will result in a higher reflectivity than the one that has more small drops and less large drops. In terms of the R-Z relationship, the spectrum that has more large drops results in a lower coefficient (A) than the spectrum with less large drops, assuming a constant exponent (b).

DSD differs from one region to the next, from one storm to another, and within a storm. For instance, at a given reflectivity, more large drops are found in continental precipitation than in maritime precipitation (Tokay et. al. 2001b). The DSD exhibits characteristic differences between extra-tropical and mid-latitudinal convection. Also, there have been characteristic differences in convective and stratitform regimes in tropical convection (Houze 1997). NASA Wallops Flight Facility, located at the mid-Atlantic coast, receives extra-tropical systems in the winter, remnants of tropical cyclones and/or hurricanes in summer, as well as precipitation developed through regional convection. Here, we studied the variations of DSD at different rain regimes in two storm systems, both being springtime convection. The DSD measured by impact and optical disdrometers were compared at different rain and wind regimes. The natural variability of DSD was also studied by comparing 3 different JWD observations separated within 2 km, the size of a radar pixel used by TRMM ground validation program.

The composite DSDs for three different time periods of the March 21 rain event was constructed utilizing both JWD1 and 2DVD measurements (Figure 8). A composite DSD representing the average of three time periods was also given. The time periods were selected based on different rainfall intensities where mean rain rates were 3.6 (moderate 1), 5.3 (moderate 2), 24.2 mm hr^{-1} (heavy). According to the Glossary of the American Meteorological Society, a rain intensity of < 2.5 mm hr^{-1} is called *light* rain, while a rain intensity of > 7.5 mm hr^{-1} is referred to as *heavy* rain. Rain intensity between 2.5 and 7.5 mm hr^{-1} represents *moderate* rainfall. Comparing the composite DSDs in Figure 8, the distribution that corresponds to heavy rain had larger maximum drop size and higher concentrations of medium and large drops. The concentration of drops increases exponentially toward smaller sizes in all three 2DVD spectra (Figure 8b). The composite JWD1 spectrum at heavy rain also shows an increase in concentration towards smaller size, with a local peak at around 1.8 mm. The concentration then decreases towards smaller sizes. The lack of small drops can be attributed to the disdrometer's dead time problem. A similar trend was found in JWD1 spectrum of moderate 1 rainfall that has been collected under windy conditions. The lack of small drops in this case may be attributed to the background noise generated by the wind. The composite JWD1 spectrum of moderate 2 rainfall shows an exponential increase toward smaller sizes with a plateau in drop concentration between about 0.6 to 1.8 mm diameter; the concentration then decreases in very small drop size regime (Figure 8a).

The composite DSDs were also constructed for three time periods representing light (1.4 mm hr^{-1}), moderate (3.0 mm hr^{-1}), and heavy (9.2 mm hr^{-1}) rainfall of the April 11 rain event (Figure 9). An exponential increase towards smaller sizes (up until 1 mm) in drop concentration was evident in all rain intensities in both the JWD1 and 2DVD composites. In the absence of strong winds, neither background noise nor the disdrometer's dead time was a factor in the JWD1 spectra.

The measurements of DSD by JWD1 and 2DVD were sensitive to the wind speed. The agreement between JWD1 and 2DVD spectra was reasonable in three different selected time periods of the April 11 rain event where mean wind speeds were at around 3.5 m s^{-1} and steady (Figure 11). In contrary, a poor agreement between JWD1 and 2DVD spectra was observed in all three selected time periods of the March 21 rain event (Figure 10). When the mean wind speeds were relatively high (Figures 10a and 10c), 2DVD under sampled the number of drops in a broad drop size range somewhere between 1 to 4 mm. JWD1, on the other hand, underestimated the small drops up to 1.8 mm in diameter. For a period where mean wind speeds were relatively low, the agreement was relatively better, except for the small and large size of the spectrum (Figure 10b). The maximum drop diameter was also larger in 2DVD than JWD1 in the DSD spectra of March 21, but this was not the case in the DSD spectra of April 11.

The discussion presented in section 3 and 4a demonstrated the natural variability of rainfall when disdrometers were separated at certain spaces within a radar pixel of 2 x 2 km. The DSD measurements by JWDs at three different sites were averaged for three selected time periods of the March 21 rain event to further diagnose variability of rainfall (Figure 12). The concentration of the drops was almost indistinguishable between 2 to 4 mm diameters while variability existed at both ends of the spectrum. Since reflectivity is the sixth moment of drop size, the variability of DSD at larger drop sizes is more important. The presence of relatively more large drops in JWD2 resulted in about 1 to 1.7 dB higher reflectivities than JWD1. The reflectivities calculated from the JWD4 spectra differed less than 0.5 dB from the reflectivities calculated from JWD1 spectra. It should be noted that the differences in reflectivities were insignificant when all the disdrometers were collocated prior to March 21 rain event.

c. Wind Effects on 2DVD

When a drop falls into the 2DVD, its position (i.e. central pixel) is recorded twice as a 2-dimensional array with a pixel number ranging from 0 to 511. The difference in the position of the drop between two planes demonstrates the wind effect on the drop. The horizontal wind speed extracted from the position of the drop in two planes is a function of the mass of the drop and therefore should not be compared to the absolute wind measurement by a sonic anemometer. If the winds blow parallel to front (side) view of the 2DVD, the drops will accumulate at the opposite end of the front (side) view while a lack of drops is typically observed at the near end of the front (side) view of the 2DVD. The distribution of the drops will then be heavily skewed across side (front) view. If the winds blow diagonally to the plane of the 2DVD, then drops will accumulate at the opposite corners such that the distribution is skewed in both front and side view of the disdrometer.

The underestimation of rainfall by 2DVD is further investigated by assessing the wind effects at four different rainfall and wind regimes. During early morning showers of the long lasting March 21 rain even where 1-minute averaged wind speeds exceeded 8 m s^{-1}, the distribution of drops were skewed in both front and side view of the 2DVD (Figure 13a). The 2DVD recorded only 0.6 mm of rain in 23 minutes at which the nearby rain gauge had a rain total of 5.1 mm. The rain total of 2DVD was recalculated by monotonically decreasing the sample area from the end where the least number of drops were recorded. This process was repeated for both side and front view of the 2DVD. Since the drops were mostly skewed in the side view, the rain total increased up to around 1.4 mm when the first 400 pixels were eliminated. Nevertheless, there is still a substantial gap (3.7 mm) between 2DVD and rain gauge totals. A numerical study including the trajectory of raindrops under windy conditions is suggested to further investigate the gap between 2DVD and rain gauge rain totals. However, this is beyond the scope of this study.

At a later time period of the March 21 rain event, where winds were relatively weak (< 4 m s^{-1}), the raindrops were equally distributed along the front view while they were slightly skewed along the side view (Figure 13b). The rain total of 2DVD was 2.7 mm, 1.6 mm less than the nearby gauge rain total. The elimination of the first 200 pixels along the side view increased the rain total to about 3.0 mm. In another time period where rainfall was more intense and winds were at around 7 m s^{-1}, distributions of the drops were again skewed in both the front and side views of the 2DVD (Figure 13c). The rain totals of 2DVD and of rain gauge in this period were 2.8 and 9.9 mm, respectively. The rain total of 2DVD recalculated by monotonically decreasing the sample volume in the side view first increased up to 4.2 mm and then decreased down to 2 mm. On the other hand, the recalculated rain total continuously increased up to 6.0 mm as the sample volume monotonically decreased in the front view. The different behavior of rain totals in front and side view may be attributed to the fact that rainfall is proportional to the third to fourth moment of the drop size, therefore the position of the large drops plays an important role in monotonically decreasing the sample volume. During a short, but intense rainy period of the April 11 rain event where wind speeds were under 4.0 m s^{-1}, drops were equally distributed in both side and front view of the 2DVD (Figure 13d). The rain totals of 2DVD and rain gauge agreed quite well and the monotonic decrease of the sample volume of 2DVD did not show any noticeable difference in rain totals.

d. X-POL Radar Analysis

Despite time height ambiguity and the differences in sample volume, the disdrometer is often employed to calibrate radar. Partial beam filling of the radar volume and radar attenuation at high frequencies also contribute to the measurement differences between the radar and disdrometer. Partial beam filling occurs since the radar beam does not cover 100% of the measured volume. Attenuation is a decrease in signal strength in transmission from one point to another. In this study, these two factors were minimal. Since the radar measurements were taken about 113 m above the disdrometer site, it will take about 56 s for a raindrop of 0.5 mm in diameter to reach the surface (Table 2). A drop of 3 mm diameter, on the other end, reaches the ground in 16 s. The disdrometer measurements are collected every minute and time delay was not a factor when comparing the disdrometer and radar measurements. The sample volume of X-POL radar at the disdrometer site is about 4.1 x 10^5 m^3, much larger than the disdrometer sample volume. The disdrometer sample volumes were presented for a one-minute sampling time and for a given size in Table 2. Considering the uniform distribution of drops of 0.5 mm in diameter, one should average 474 days of the disdrometer record to match the sample volumes of the disdrometer and X-POL radar. If the disdrometer sample volume is composed of drops 3 mm in diameter, then the disdrometer record should average for 119 days. In practice, the disdrometer record is averaged following (13) to match with the sampling area of the X-POL radar. Zawadzki (1975) presented this empirical relationship between radar sampling area (*RA*) and disdrometer and/or rain gauge averaging period (*t*) with an assumed advection velocity (*v*) given as:

$$t = \frac{1.3\sqrt{RA}}{v} \qquad (13)$$

The X-POL radar sample area at the disdrometer is about 2.8 x 10^4 m^2. For a 1-minute averaging time period for disdrometer , this corresponds to a 13 km hr^{-1} advection speed. If the storm is moving faster than this advection speed, then a shorter time period will be needed for disdrometer averaging (< 1 minute), and vice versa is true if the storm is moving slower. In windy conditions, drop trajectories can be slanted substantially. For instance, a raindrop of 1 mm diameter falling at its terminal fall speed will reach the surface with a 108 m deviation from its vertical position in the presence of 13 km hr^{-1} wind speed. This has been illustrated in Figure 14.

The X-POL measurements of Z_H and ZDR were compared to those directly calculated from the JWD utilizing equilibrium and observed drop axis ratios (Andsager et al. 1999) The disdrometer calculations were performed at 3.2 cm wavelength, but Rayleigh scattering approximation rather than Mie scattering was employed. This should be count as one of the sources of error in radar and disdrometer comparisons. The time series of Z_H calculated from observed and equilibrium drop shapes were almost identical indicating its insensitivity to the drop shape (Figure 15a). Also, a good agreement was evident between disdrometer and radar horizontal reflectivity (Figures 15a and 15b). The differential reflectivity that has been calculated for observed drop shapes is lower than that calculated for equilibrium axis ratios (Figure 14c). Also, there is a bias between radar and disdrometer ZDR measurements. Unlike Z_H, the histogram of ZDR derived for X-POL radar and disdrometers exhibit substantial differences such that disdrometer ZDR had higher readings than radar ZDR, on average (Figure14d).

5. Summary and Conclusions

Four months (January to April 2001) of surface rainfall measurements were analyzed to evaluate instruments performance in measuring rainfall and to investigate natural variability of rainfall. The rainfall measurements were collected by optical and impact disdrometers and rain gauges at the NASA Wallops Flight Facility. For a two-month period, an X-band polarimetric radar also provided surface rainfall estimates right above the surface data acquisition network. Sonic anemometers were also in part of the network and helped to diagnose the measurement errors of the disdrometers. The following conclusions may be drawn from the analysis presented above:

a) A very good agreement was evident between RG1 and RG2 rain totals while RG3 had relatively low readings. Although all the three gauges were nearby to each other, RG3 was relatively distant from the first two rain gauges, therefore natural variability may have played a role in differences of rain accumulation.
b) When all four JWDs were nearby to each other, the rain totals were within 4 to 8% of each other on average with standard deviations of 10 to 12%. When disdrometers were separated, the means in rain totals were 5 to 12% with standard deviations of 13 to 21%, indicating variability of rainfall within a typical radar pixel.
c) The JWD underestimated the rainfall 6 and 10% with regard to RG1 and RG2, respectively, while it overestimates 5% with respect to RG3. Similarly, 2DVD underestimates the rainfall ranging from 9 to 17% when its rain total was compared with the three nearby gauges.
d) Wind was the leading factor in determining agreement between disdrometer and rain gauge rain totals. A case study taken in windy conditions showed poor correlations between the disdrometers and rain gauge rainfall such that optical disdrometers severely underestimated the rainfall. A much better agreement of disdrometer and gauge rain totals was evident in relatively light wind conditions.
e) Rainfall time series derived from disdrometers separated within 2 km showed differences in intensity and a shift and of local rain maxima. This has been consistent with the direction of the storm movement.
f) Wind was also the leading factor for the discrepancy of the DSD between optical and impact disdrometers. The number of drops was severely underestimated between 1 to 4 mm in diameter by 2DVD. JWD, on the other hand, underestimated small drops due to the background noise generated by the wind as well as the disdrometer's dead time problem. The JWD was also not able to detect drops larger than 5.0 to 5.5 mm in diameter.
g) The composite DSDs derived from two JWDs separated by 650 m resulted in 1 to 1.7 dB differences in reflectivities in a windy rain event. This is due to the presence of more large drops in one of the two disdrometers. The composite DSDs derived from two disdrometers separated by 1.7 km, however, exhibited less than 0.5 dB differences in reflectivity for the same period of the rain event.
h) 2DVD is an unreliable instrument under windy conditions. This is mainly due to its design such that the instrument itself is a barrier to the incoming precipitation. This has been shown by examining the distribution of the drops in sample area in windy conditions. The rain accumulation calculated for a decreased along the wind direction sample area differed from that calculated for the 2DVD sample area.
i) The disdrometer sampling time of 1-minute seems to be appropriate for a X-POL radar rainfall and disdrometer rainfall comparison since the X-POL radar was only 3.8 km from the disdrometer site and had a beam width of 0.9°. However, raindrop trajectories can be severely slanted under windy conditions so that one should not expect quantitative agreement between X-POL radar and disdrometer measurements.

j) Z_H was insensitive to the variations of drop shape, while ZDR had lower readings when observed rather than equilibrium axis ratios were employed.
k) A good agreement was evident between the X-POL radar and disdrometer horizontal reflectivities. The X-POL radar, on the other hand, had lower ZDR readings than the disdrometer.

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