Microphysical Properties of Maritime Squall Line Observed on June 2, 2008 in Taiwan

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Abstract

The physical characteristics of rain are reflected by the shape of the raindrop size distribution (RDSD). Specifically, the RDSD is the result of different precipitation formation processes. We measured the RDSD at the surface in heavy rainfall during SoWMEX/TiMREX (2008) in Taiwan. The heavy rainfall was characterized by a squall line accompanied by trailing stratiform precipitation, and it was partitioned into three regions based on radar reflectivity patterns: convective line, stratiform, and reflectivity trough. The convective line was further partitioned into the convective center, leading edge, and trailing edge using a threshold rainfall intensity of 20 mm h⁻¹.

The leading edge, which belongs to the convective line, had upward motion from the surface and contained many small drops. The leading edge was characterized by a small median volume diameter (D_0) and a linear shape of gamma RDSD. In the convective center, a strong updraught rose to the top of the cell with time, and many large drops over 4 mm were observed. The convective center, which had large D_0 and normalized intercept parameter (N_W), was characterized by an upward convex shape of gamma RDSD. The range of raindrop diameter decreased toward the trailing edge, with no updraught or only weak updraughts at high altitudes. The trailing edge had large shape and slope parameters, along with a more upward convex shape of gamma RDSD. A bright band was observed in the stratiform region with continual downward motion from the bright band to the surface, even though the intensity became weak. In the stratiform region, D_0 and N_W were small and the gamma RDSD had an upward convex shape.

The different RDSDs in each region of a maritime squall line suggest the existence of different cloud microphysical processes described by the change of RDSD parameters: the coalescence process induces an increase of D_0 and shape parameter and a decrease of N_W , while the break-up process induces a decrease of D_0 and an increase of N_W .

In comparison with other maritime storms, the convective center has small $\log_{10}N_W$ and large D_m value. And the convective edge region is positioned between convective center and stratiform region in the D_m - $\log_{10}N_W$ scatter plot.

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1. Introduction

The raindrop size distribution (RSD) is the end product of all the cloud microphysical processes, cloud dynamic processes, and interactions that affect the formation and growth of liquid precipitation, since the variability of precipitation is directly linked to the variance of RSD in space and time (Willis 1984). The RSDs associated with different precipitation types (e.g., convective and stratiform rain) and origins of development (e.g., continental and maritime) can be characterized by range of raindrop diameter, concentration, and RSD shape, which can reflect the physics of rain through analytic forms, such as gamma or normalized gamma distributions (Ulbrich 1983; Testud et al. 2001).

Recent RSD studies have been carried out by investigating the differences between convective rain and stratiform rain with regard to the origin of their development. The RSD in a convective center is characterized by an upward convex shape with large median volume diameter (D_0), whereas the RSD in a stratiform region is characterized by a more exponential shape with small D_0 in maritime storms (Atlas et al. 1999). The RSD from stratiform rain is consistent with microphysical processes occurring within an aggregation/melting layer aloft, which produces larger raindrops and fewer median size raindrops than the RSD from the convective rain at the same rainfall rate. Tokay and Short (1996) and Testud et al. (2001) presented an empirical stratiform-convective classification method based on RSD parameters. For different climatic regions, on average, two parameters (D_m and normalized intercept parameter N_W) of stratiform rain are nearly linearly related, with a negative slope, which appears to be consistent with variations in the microphysics of stratiform rain. Maritime-like convective rain was clustered around $\langle D_0 \rangle = 1.54$ to 1.75 mm and $\log_{10} \langle N_W \rangle = 4$ to 4.5 with both shape parameter (μ) and slope parameter (λ) extending over a broader range (Bringi et al. 2003; Ulbrich and Atlas 2007). In order to investigate the microphysical mechanisms of precipitation and their association with RSD, a dynamic approach is necessary. However, it is hard to obtain dynamic data with high spatial-temporal resolution.

The squall line convective system had a distinctive structure, which consisted of a leading line, trailing stratiform, and reflectivity trough. According to Smull and Houze (1987), the convective line is defined as the leading line of deep convection that exhibits an organized multicellular structure. The trailing strati-

form features a radar bright band at the melting level. These contrasting radar echo regimes are separated by a narrow band of weak reflectivity at the lower levels, termed the transition zone. The transition zone defined by Smull and Houze (1987) is very similar to the “reflectivity trough” described by Sommeria and Testud (1984). The conceptual model of the two dimensional hydrometeor trajectories through the stratiform region of a squall line with trailing stratiform precipitation proposed by Biggerstaff and Houze (1991) shows that the stratiform was formed by ice particles that were supplied by the convective region. The stratiform region has a secondary maximum precipitation region and is characterized by a mesoscale updraft in the upper troposphere and a mesoscale downdraft in the lower atmosphere. According to Tao et al. (1991), the dynamic and kinematic structures of the subtropical squall line that occurred during TAMREX (Taiwan Area Mesoscale Experiment) are quite similar to its counterparts observed in the tropics and mid-latitudes.

The Taiwan meteorological community conducted a joint US-Taiwan multi-agency field experiment during the period of May 15 to June 30, 2008, in southern Taiwan, called the Southwest Monsoon Experiment/Terrain-influenced Monsoon Rainfall Experiment (SoWMEX/TiMREX). On June 2, 2008, a squall line convective system hit the southwestern part of Taiwan, causing severe disasters such as flooding and land slides. During the passage of the convective system, SoWMEX/TiMREX successfully observed the precipitation with fine resolution.

The object of this work is to identify the characteristics of RSD in this system, and to relate the characteristics to the microphysical processes. A comparison with other maritime storms was conducted. In the next section, we will describe the data and methods used in this study. Case description and RSD that statistically characterize the leading edge, convective center, trailing edge, and stratiform regions, including the results of hydrometeor classification will be shown in Section 3. In Section 4 the microphysical processes of this case will be discussed and RSD properties will be compared to other maritime storms. We will summarize the results and conclusion in Section 5.

2. Data and method

Taiwan has unique topography composed of mountains over 3,000 m high from the north to the south of the eastern part of the island and of large oblique downward coastal plains to the west coast, with a horizontal distance of about 100 km from the western coast to the mountainous area. In the summer season, the

Fig. 1. Elevation map of Taiwan, with observed domain indicated by black solid rectangle. POSS and VertiX are located in the super-site (22.73°N, 120.62°E), and the S-band polarimetric radar (22.52°N, 120.43°E) is denoted by the pentagram and circle, respectively.

lower moisture supplied by the southwest monsoonal flow, combined with the complex terrain, leads to heavy precipitation.

To improve understanding of the physical and microphysical processes associated with the terrain-influenced heavy precipitation systems and the monsoonal environment, SoWMEX/TiMREX (Jou et al. 2011) was held in the western plain and mountain slope region of south Taiwan from May 15 to June 30, 2008.

During this field experiment period, the raindrop

size distribution in a maritime squall line system was observed by POSS (Precipitation Occurrence Sensing System, Sheppard et al. 1994), and the microphysical characteristics of precipitation were analyzed using VertiX (vertical pointing X-band radar, Zawadzki et al. 2001) and S-Pol (S-band polarimetric radar, Keeler et al. 2000) on June 2, 2008.

2.1 Observation data

POSS is a bistatic X-band (10.25 GHz, 2.85 cm) Doppler radar operating at low power and continuous wave. When a raindrop passes the POSS measurement volume, a voltage signal is generated with a frequency proportional to its Doppler velocity and amplitude that is a function of the drop size and its location in space. Therefore, when the drop is falling, the signal generated varies in frequency and amplitude. POSS measures the Doppler power density spectrum $S(f)$, which is a weighted moment of the RSD, and the number density $N(D)$ for a drop diameter of D mm is calculated with a discrete approximation assuming a certain fall velocity.

The number of diameter bins is 34, from 0.34 mm to 5.4 mm. The diameter intervals (dD) increase with diameter (e.g., $dD = 0.5$ mm at $D = 0.34$ mm and $dD = 1.84$ mm at $D = 5.4$ mm). The number density at $D = 5.4$ mm includes the number of all drops larger than this diameter. POSS has been carefully calibrated by measuring a precise beam pattern, through simulations and has been further validated with other disdrometers and rain gauges (Sheppard and Joe 1994; Jang et al. 2004; You et al. 2004, 2009; Sanchez et al. 2005; Lee and Zawadzki 2005, 2006). The sampling volume is three orders of magnitude larger than that of other disdrometers, so that under-sampling is a second order problem in POSS. Most conventional disdrometers have difficulty in measuring big drops due to the small sampling volume. However, due to its large sampling volume, bigger drops are measured well with POSS (Sheppard and Joe 1994). POSS estimates the RSD from the characteristics of the scattered power received from drops in a defined measurement volume assuming each drop size produced power at a single Doppler frequency corresponding to its terminal velocity. The surrounding velocity of POSS has influenced the estimated RSD (Sheppard 2007). In the scatter plot of rainfall intensity measured by collocated rain gauge and calculated by POSS (Fig. 4), the coefficient of determination (R^2) and slope were 0.88 and 0.87, respectively. It was considered that rainfall intensities by POSS were underestimated and shown as errors due to strong wind associated with squall line.

As shown in Fig. 1, the X-band vertical pointing radar was located at a super-site with POSS. Despite its simplicity and its fixed pointing direction, very detailed radar images can be obtained when a weather system passes overhead. At this point, the radar can detect all precipitation targets, some ice clouds, clear air targets (insects and birds), and the turbulence associated with developing cumulus clouds. VertiX is exclusively and widely used for research; in particular, for in-depth study of the melting layer of precipitation (Fabry and Zawadzki 1995; Gourley and Calvert 2003), the detection of super-cooled water (Zawadzki et al. 2001), estimation of vertical air motions (Geerts et al. 2006), and snow microphysical processes (Surcel and Zawadzki 2010).

S-Pol was installed in the southwestern coastal plain of Taiwan (Fig. 1). S-Pol, which covers a radius of 250 km around the southwestern part of Taiwan, records sets of volume reflectivity scans, Doppler velocity, and polarimetric parameters every 7.5 min. The sampling resolution of the radar data is 500 m in the radial direction and 1.0° in the azimuthal direction. Each volume scan consists of 9 elevation angles (0.5° , 1.1° , 1.8° , 2.6° , 3.6° , 4.7° , 6.5° , 9.1° , and 12.8°), each PPI (plan-position indicator) scan consists of 13 elevation angles (1.0° , 1.9° , 2.7° , 3.6° , 4.4° , 5.3° , 6.1° , 7.0° , 7.8° , 9.6° , 12.0° , 15.0° , and 18.0°) and each RHI (range-height indicator) scan consists of 16 azimuthal angles (11.0° , 15.0° , 26.5° , 32.0° , 33.5° , 35.0° , 36.0° , 37.0° , 38.0° , 39.0° , 4.0° , 41.0° , 43.0° , 45.5° , 57.0° , and 60.0°).

2.2 Analysis method

a. Functional form of RDSD and method for estimating its parameters

The gamma distribution function (Ulbrich 1983) and the normalized gamma distribution function (Testud et al. 2001) were used to parameterize the RDSD in this study. The RDSD could be well described by a gamma distribution function of the form,

$$N(D) = N_0 D^\mu \exp(-AD) \quad (1)$$

where $N(D)$ is the number density of raindrops with diameter interval D to $D + \delta D$ in a given volume of air. N_0 , A , and μ are the intercept, slope, and shape parameters, respectively. Normalizing the distribution removes the dependence on N_0 and A in Eq. (1), which allows the comparison of distribution shapes for different rainfall rates (Willis, 1984). The normalized gamma distribution form is

$$N(D) = N_w f(\mu) (D/D_0)^\mu \exp(-(3.67 + \mu)(D/D_0)) \quad (2)$$

with

$$f(\mu) = \frac{6}{3.67^4} \frac{(\mu + 3.67)^{\mu+4}}{\Gamma(\mu+4)} \quad (3)$$

where N_w ($\text{mm}^{-1}\text{m}^{-3}$) is the normalized intercept parameter, D_0 is the median volume diameter, and $f(\mu)$ is the normalized shape of the RDSD. The parameters of the gamma distribution were retrieved using a moments approach (Kouz and Nakamura 1991). The RDSD moments that contain important physical information are calculated and analyzed based on the simulated RDSDs.

$$M_x = \int_{D_{\min}}^{D_{\max}} D^x N(D) dD \quad (4)$$

Using 3, 4, and 6 moments, the gamma RDSD parameters are obtained as shown in Table 1. Obviously, the RDSD parameters are nonlinear functions of the RDSD moments. Since the moment estimators (M3, M4, and M6) contain measurement errors due to system noise, truncation of measured RDSD or finite sampling; the estimated gamma RDSD parameters also have error. Even if the moment estimators were determined precisely, the estimated RDSD parameters would fluctuate due to the fact that natural RDSDs may not exactly follow the assumed gamma distribution (Zhang et al. 2003). In this study, the biases of RDSD parameters are not considered (for more detailed error propagation from moment estimators to RDSD parameter estimators, see Zhang et al. 2003).

c. Classification of precipitation type

Separation of the convective-line, reflectivity-trough, and stratiform regions involved a three-step procedure using 1) PPI images of reflectivity, 2) time series of vertical reflectivity and radial velocity, and 3) time change of rainfall rate observed by disdrometer. First, the times of occurrence in each region were roughly identified based on examination of 8-min. interval PPI images from the S-band polarimetric radar. The convective region had a line shape with high reflectivity. The stratiform region followed the convective line. The reflectivity-trough region had a reflectivity minimum between the convective line and the stratiform region. Next, the time series of vertical reflectivity and radial velocity from VertiX was used to identify the stratiform region. The stratiform region had a bright band and no updraught, while a high altitude echo with updraught appeared in the convective region. Finally, using the threshold rainfall rate measured by

Table 1. RSDS parameters.

Parameter	Equation
Rainfall intensity	$R = \frac{\pi}{6} \int_{D_{\min}}^{D_{\max}} D^3 V_f N(D) dD$
Reflectivity	$Z = \int_{D_{\min}}^{D_{\max}} D^6 N(D) dD$
Shape	$\mu = \frac{(8-11m)-(m^2+8m)^{1/2}}{2(m-1)}$ $m = \frac{M_4^3}{M_3^2 M_6}$
Slope	$A = \frac{M_3}{M_4} (\mu + 4)$
Median volume diameter	$D_0 = \frac{(3.67 + \mu)}{A}$
Mass-weighted mean diameter	$D_m = \frac{(4 + \mu)}{A}$
Intercept parameter	$N_0 = \frac{A^{(\mu+4)} M_3}{\Gamma(\mu+4)}$
Generalized intercept parameter	$N_w = \frac{N_0}{f(\mu)} D_0^\mu$

POSS, the convective line was subdivided into three regions: the convective center (CC), leading edge (LE), and trailing edge (TE) of the convective line. We defined the convective center as the strongest part of the convective line, which had to achieve a threshold rainfall rate of 20 mm h⁻¹. The leading edge and the trailing edge were defined as the front and rear sides of the convective center, respectively. The threshold value of 20 mm h⁻¹ corresponds to a radar reflectivity of 42 dBZ when the ZR relationship that is applied for convectional rain by Woodley et al. (1975) and Gagin et al. (1985) is used. Tokay and Short (1996) found that all convective spectra measured by a disdrometer had a rainfall rate greater than 20 mm h⁻¹. Maki et al. (2001) used a threshold value of 20 mm h⁻¹ when they classified the convective center in the convective line of a continental squall line observed in Darwin, Australia. Samples having rainfall rates less than 0.05 mm h⁻¹ were excluded from the analysis since data with very low rainfall rate sometimes cause large scatter in RSDS characteristics.

3. Results

3.1 Case description

On June 2, 2008, maritime squall line systems hit the southwestern part of Taiwan from 0448 UTC to 0946 UTC. The accumulated rainfall amount calculated by POSS was recorded as 35.8 mm on the super-site. The system moved in an easterly direction and was partitioned into convective and stratiform regions based on the horizontal and vertical reflectivity pattern, vertical radial velocity, and rainfall intensity at the super-site. The time of each classified region of the system is presented in Table 2.

The first convective line was observed at the western side of the super-site at 0446 UTC (Fig. 2a), and Fig. 3 shows that a high-altitude echo with reflectivity over 35 dBZ had started and the updraught rose as time passed; the same time as in Fig. 2a. At 0523 UTC (Fig. 2b), the super-site was covered with weak reflectivity and a bright band was detected by VertiX (Fig. 3).

The convective cell behind the first convective line was recorded at the super-site at 0538 UTC, and then weak reflectivity with a bright band (Fig. 3) followed the convective cell (Figs. 2c, d).

Table 2. Classified times in each analyzed region of maritime squall line observed in June 2, 2008.

Date	Leading edge (UTC)	Convective center (UTC)	Trailing edge (UTC)	Stratiform (UTC)
2 June 2008	0448–0450	0451–0508	0509–0520	0521–0531
	0532–0540	0541–0542	0543–0554	0555–0606
	0627–0636	0637–0641	0642–0713	0714–0738
	0739–0747	0748	0749–0750	0751–0946

The second convective line was recorded at the super-site at 0638 UTC (Fig. 2e), and then weak reflectivity with a bright band (Fig. 3) covered a large area and lasted for 3 hours from 0700 UTC to 0948 UTC. Within the stratiform region (Figs. 2f, h), a convective cell developed and the edge of the convective cell passed over the super-site at 0745 UTC (Fig. 2g).

Figure 3 shows the time-height profile of radar reflectivity and radial velocity measured by VertiX. The reflectivity value was not analyzed in previous studies since it is widely known that radar signal attenuation occurs due to the scattering and absorption of rain drops under heavy precipitation condition, particularly with the X-band wavelength radar (Kim et al. 2008). The radial velocity is the sum of the reflectivity-weighted particle fall speed and the vertical air motion.

In the convective lines (around 0452 UTC and 0640 UTC), a region of strong downdraught (purple to yellow) with a radial velocity of over -12 m s^{-1} was detected, coinciding with the highest rainfall intensity (95 and 100 mm h^{-1}) observed by POSS at the surface. In the first convective line, from 0500 UTC to 0510 UTC, a strong updraught, which had a maximum radial velocity of over $+10 \text{ m s}^{-1}$, rose from a height of 6 km to 9 km; and a strong downdraught, with a maximum radial velocity of over -12 m s^{-1} was presented from 6 km down to the surface as time passed. In the second convective line, from 0640 UTC to 0650 UTC, an updraught with a maximum radial velocity of over 6 m s^{-1} rose from a height of 3 km to 8 km as time passed, and a downdraught appeared from a height of 5 km to 2 km. The convective cells behind the first convective line and in the stratiform region had a weak updraught with a maximum radial velocity of over $+2 \text{ m s}^{-1}$ above 5 km. In the convective cell, the downdraught was located below 2 km (0540 UTC) and 4 km (0545 UTC) in height.

In the stratiform region, the bright band was located at 4.5 km, and downdraughts were continually measured under the bright band. In particular, strong downdraughts appeared at 0720–0730 UTC and 0810–

0845 UTC.

3.2 RDSD analysis

The time series of the RDSD is shown in Fig. 5. Many large drops over 3 mm in diameter were observed in the convective and stratiform regions, which followed the second convective line. Large numbers of small drops and small numbers of large drops were observed in the leading edge of the convective lines. The convective centers had many drops in the 1–2 mm diameter range, represented in red, and large drops over 4 mm in diameter had a high number density compared with other regions. The two convective lines had a similar rainfall intensity of almost 100 mm h^{-1} , however, the RDSDs are different; the first (second) convective line had many small (large) drops compared with the second (first) convective line. In the convective lines, RDSDs, including large drops with a maximum diameter of 5.4 mm, were measured in the convective center (0451–0508 UTC and 0637–0641 UTC) with strong up- and down-draughts in the VertiX images (Fig. 3). The measured maximum diameter decreased gradually toward the trailing edge. In the stratiform region behind the first convective line, the measured maximum diameters were smaller than in the first convective region, whereas the stratiform region behind the second convective line contained large diameter raindrops similar to those in the convective region, and small raindrops less than 1 mm in diameter disappeared during 0720–0735 UTC and 0820–0850 UTC.

The time series of rainfall intensity, reflectivity, D_0 , and N_0 is shown in Fig. 6. All of the parameters were calculated using the disdrometer data. The highest rainfall intensity in the first convective line was recorded as 95.07 mm h^{-1} with 51.95 dBZ of reflectivity at 0451 UTC. The maximum rainfall intensity and reflectivity were 100.2 mm h^{-1} and 52.93 dBZ in the second convective line at 0640 UTC. The convective region had a large D_0 value compared with the stratiform region, and the convective center had a small N_0 value compared with the leading and trailing edges, except

Fig. 2. PPI of reflectivity at each elevation (a) 1.47° at 0446 UTC, (b) 1.50° at 0523 UTC, (c) 1.07° at 0538 UTC, (d) 1.07° at 0553 UTC, (e) 1.08° at 0638 UTC, (f) 1.51° at 0723 UTC, (g) 1.51° at 0745 UTC, and (h) 1.51° at 0808 UTC. The small black quadrangle and circle show the locations of the S-band polarimetric radar and the super-site, respectively.

Fig. 3. Time series of reflectivity (upper) and radial velocity (bottom) observed by VertiX in the super-site from 0440 UTC to 1000 UTC on June 2, 2008.

Fig. 4. Scatter plot of rainfall intensity calculated by POSS and measured by collocated rain gauge.

for the convective cell within the stratiform region following the second convective line. The stratiform region following the second convective line had quite large D_0 and small N_0 values at 0717–0730 UTC and 0810–0900 UTC, and those periods were matched by downdraught regions in VertiX.

The characteristics of the RDSD shapes of the leading edge, convective center, trailing edge, and

stratiform region and the corresponding gamma RDSD fits are shown in Fig. 7. The times corresponding to these RDSDs are indicated by black triangles along the x-axis in Fig. 5. The gamma RDSD function fit the observed data well in all regions. The RDSD for the leading edge was characterized by a linear shape with small raindrops. The RDSD for the convective center was characterized by an upward convex shape with the largest $N(D)$ near $D = 1$ mm and large raindrops ($D > 4$ mm). The RDSD in the trailing edge was characterized by an upward convex shape, which was similar to the RDSD shape for the convective center. However, $N(D)$ was much smaller than that observed in the convective center. Large raindrops also existed in the stratiform region, but were fewer in number than in the convective center.

Figure 8 shows RDSDs for each region. The gray line is the averaged RDSD and the black line is the averaged gamma RDSD. The averaged values of the RDSD parameters for each region are shown in Table 3. For the leading edge (Fig. 8a), the averaged gamma RDSD is represented by a linear shape with the smallest D_0 . The averaged gamma RDSD of the convective center is represented by a slightly upward convex shape with a gentle slope and the largest D_0 and N_W . For the trailing edge, the distribution has a convex shape as the number density began to decrease for diameters under 1 mm. Moreover, the averaged RDSD and gamma RDSD are represented by a more upward convex shape with steep slopes. Finally, the stratiform consisted of many medium and small drops, but the

Fig. 5. Time series of disdrometer-based rain intensity (black solid line) and 1-minute number density of raindrops from 0440 UTC to 0946 UTC on June 2, 2008.

Fig. 6. Time series of disdrometer-based rain intensity (vertical bar), reflectivity (gray solid line), D_0 (black solid line), and N_0 (black dotted line) from 0440 UTC to 0946 UTC on June 2, 2008.

number density of raindrops was smaller than in the other regions. Therefore, the averaged RDS and gamma RDS for the stratiform region are represented by a convex shape with smaller N_W .

3.3 Polarimetric radar analysis

To examine the relation between RDS and hydrometeor type, the National Center for Atmospheric Research (NCAR) Particle Identification Algorithm (PID) (Vivekanandan et al. 1999) was used to determine hydrometeor types. The NCAR PID is a multi-pa-

rameter fuzzy logic algorithm used to determine the most dominant scatter in the radar pulse resolution volume or range gate (Vivekanandan et al. 1999). The algorithm requires 6 inputs, namely, dual polarimetric radar variables (reflectivity at horizontal polarization (Z_H), differential reflectivity (Z_{DR}), linear depolarization ratio (LDR), correlation coefficient (ρ_{HV}), specific differential phase (K_{DP}); for a review of these variables, see Bringi and Chandrasekar, 2001), and the temperature profile. The PID classifies the hydrometeor into 17 categories as follows: cloud droplets, drizzle, light

Fig. 7. Different RDSDs of the maritime squall line on June 2, 2008, observed in Taiwan. Values of RDSD parameters (R , N_0 , A , and μ) in for the leading edge (LE; 0634 UTC), convective center (CC; 0452 UTC), trailing edge (TE; 0709 UTC), and stratiform (SS; 0807 UTC) regions are (2.5, 1.18×10^5 , 5.8, 1.5), (62.1, 2.14×10^5 , 4.5, 3.8), (4.0, 8.4×10^7 , 12.3, 12.4), and (3.8, 2.64×10^4 , 4.5, 2.6), respectively. The values of N_0 are model values.

rain, moderate rain, heavy rain, hail, rain/hail, graupel/small hail, graupel/rain, dry snow, wet snow, ice crystal, irregular ice crystal, super-cooled liquid water droplet, insects, second trip echo, and ground clutter.

The RHI reflectivity and hydrometeor classification results of S-Pol for the first convective line at 0506 UTC, the convective cell in the stratiform region at 0744 UTC, and the stratiform region at 0814 UTC are shown in Fig. 10. The super-site was located about 28.7 km from the S-Pol radar.

At 0506 UTC, the top of the cell (10 dBZ reflectivity) reached to an altitude of 14 km, with values stronger than 40 dBZ from the surface to 5 km above the super-site. The leading convective cell was composed of moderate rain below the melting level with some heavy rain between 0.5 km and 3.5 km and graupel above, up to 8 km, but dry snow was mainly observed on the super-site. Dry snow and irregular ice crystals were found in the upper levels. The graupel column corresponds to the strong updrafts from 0502 UTC to 0510 UTC in Fig. 3, which could be responsible for lifting rain drops and producing graupel. Afterward, the relatively large fall speeds of graupel particles (2–4 ms^{-1}) cause the strong downdrafts under a region of strong updraft from 0502 UTC to 0510 UTC.

During that period, the time series of the RDSD (Fig.

5) shows that the values of the number density values for diameters over 3 mm approximately increased by a factor of ten, and small raindrops under 1 mm in diameter decreased or disappeared. Moreover, the shape of the RDSD changed to an upward convex shape with a gentle slope in comparison with the earlier period from 0453 UTC to 0501 UTC (not shown). In addition, the averaged RDSD parameters were changed, with an increase of μ (from 5.83 to 7.17) and D_0 (from 1.85 mm to 2.43 mm) and a decrease of A (from 5.19 to 4.52) and $\log_{10}N_0$ (from 5.82 to 7.17), although the averaged rainfall intensity remained almost the same, 22 mmh^{-1} . It is considered that the coalescence process was predominant in the period from 0502 UTC to 0510 UTC, when a thick graupel column was measured above the melting layer (detailed discussion was performed in section of 4.a Identification of microphysics using RDSD).

At 0744 UTC, the height of the reflectivity over 10 dBZ is 10 km, and maxima greater than 25 dBZ are seen below 7 km and greater than 40 dBZ below 5 km. The convective cell in the stratiform region is composed of moderate rain and wet snow just below the melting layer. Dry snow and ice crystals are found in the upper levels. Graupel/small hail and graupel/rain are observed at heights from 3.5 km to 5.5 km on the super-site. The graupel regions match the updraft, which appeared at 4.5–6 km from 0740 UTC to 0750 UTC, as recorded by VertiX (Fig. 3). In the same period, the number density of raindrops of over 1 mm in diameter increased. The averaged gamma RDSD appears as a more upward convex shape ($\langle\mu\rangle = 3.66$, $\langle A\rangle = 4$, $\langle D_0\rangle = 1.8 \text{ mm}$, and $\langle \log_{10}N_0\rangle = 4.29$) than previously.

At 0814 UTC, the height of the reflectivity (10 dBZ) is 8.5 km, with the bright band (stronger than 40 dBZ) at an altitude of 4.5 km. In the stratiform region, the predominant hydrometeor in the lower levels is light rain, although moderate rain is scattered throughout the light rain. Graupel located near the bright band is positioned between dry and wet snow. Although only one image is shown for the stratiform region, the graupel is presented near the bright band from 0806 UTC to 0859 UTC over the super-site in the VertiX image (Fig. 3). Comparison of the gamma RDSD shapes for the stratiform region includes graupel, with the region not including graupel shows that the stratiform region including graupel has an RDSD with a more upward convex shape ($\langle\mu\rangle = 5.13$, $\langle A\rangle = 4.72$, $\langle D_0\rangle = 1.87$, and $\langle \log_{10}N_0\rangle = 3.92$).

Smull and Houze (1987) suggested that the breadth and horizontal position of the most intense portion of

Fig. 8. RDSDs, averaged RDSD, and averaged gamma RDSD for (a) leading edge LE, (b) convective center CC, (c) trailing edge TE, and (d) stratiform SS in maritime squall line. The durations of each regime are (a) 29 minutes, (b) 21 minutes, (c) 62 minutes, and (d) 164 minutes.

Table 3. Averaged value of normalized gamma RDSD parameters in each region of maritime squall line.

	R (mmh ⁻¹)	μ	A	D_0 (mm)	N_W (m ⁻⁴)
Leading edge	7.6	5.1	5.5	1.6	5.5×10^4
Convective center	40.3	5.5	4.1	2.3	7.2×10^4
Trailing edge	8.4	9.5	8.3	1.7	4.0×10^4
Stratiform	3.5	5.9	5.9	1.7	1.8×10^4

Fig. 9. Averaged gamma RSD for leading edge LE, convective center CC, trailing edge TE, and stratiform SS at each different developmental stage in the maritime squall line, which are shown (a) from 0448 to 0531 UTC (case1), (b) from 0532 to 0606 UTC (case2), (c) from 0639 to 0738 UTC (case3), and (d) from 0739 to 0946 UTC (case4) on June 2, 2008.

the trailing stratiform precipitation may be explained by the fallout pattern of hydrometeors advected into the stratiform region by the mesoscale airflow relative to the storm. Rutledge and Houze (1987) confirmed that graupel particles from the upper portions of cells in the convective line grow by vapor deposition and collect snow generated by the mesoscale ascent. Hence, by the time they reach the melting level, they fall out as rain. Fovell and Ogura (1988), McCumber et al. (1991) and Morrison et al. (2009) found that inclusion of ice microphysics enhanced stratiform precipitation in a simulated squall line because of an increased rearward flux of hydrometeors in the presence of snow/graupel. The presence of graupel, first in the convective cell and later in the stratiform region, had been simulated

and observed by Randell et al. (1994) for tropical, continental, and oceanic storms in Darwin, Australia, by Szeto and Cho (1994) for an idealized case. And Evaristo et al. (2010) presented that the mixed layer where there is wet snow, large drops and graupel is confined around the melting layer of West African squall lines using single-polarization radar.

4. Discussion

4.1 Identification of microphysics using RSD

Rosenfeld and Ulbrich (2003) have provided schematic diagrams for the microphysical processes of precipitation using raindrop size distribution. Modification of the RSD by coalescence decreases the number of small diameter drops and increases that

Fig. 10. RHI reflectivity of S-Pol radar at (a) 0506 UTC, (b) 0744 UTC, and (c) 0814 UTC; hydrometeor classification at the same times (d), (e), and (f) at 40.9° azimuth, which is located at a range of 28.7 km from the super-site.

of larger drops. Therefore, as D_0 increases, the total number density of drops N_T decreases. The μ values also increase and vary depending on the efficiency of the coalescence process. Modification of the RDSD by break-up increases the numbers of small diameter drops and decreases the numbers of large diameter drops. There may be a consequent decrease in D_0 and an increase in N_T and N_0 , with a small change in μ . The break-up process has more influence on larger sized drops, while the coalescence process has more influence on smaller sized drops (insofar as numbers are concerned). Both processes acting together increase μ , but the level of change depends on the relative strengths of the two processes in real cloud situations. The presence of evaporation acting alone will result in a greater loss in the numbers of small diameter particles than large drops. Consequently, N_T is not constant and must decrease. There must also be a substantial change in the shape of the RDSD so that μ and D_0 increases and N_0 decreases. For further details about schematic diagrams of RDSD affected microphysical processes refer to Rosenfeld and Ulbrich (2003).

As time passed, the maritime squall line system was divided into 4 cases, including the leading edge, convective center, trailing edge, and stratiform region. For all cases (Fig. 9), the number density of raindrops less than about 1 mm decreased and the number density of larger raindrops increased from the leading edge to the convective center; therefore, D_0 and the μ value increased and N_0 decreased. From the convective center to the trailing edge, the number density of large raindrops decreased and that of small drops increased in cases 1 and 2. In case 3, the number density decreased for all diameters, but the decrease was greater for large drops, and in case 4, the number density decreased only for medium and large drops. Nevertheless, the value of the shape parameter (μ) increased in all cases. In the stratiform region, there were many drops of around 1 mm compared to smaller and larger drops, and the shape of the averaged gamma RDSD showed an upward convex shape, unless case 2 had a linear shape.

Based on the results by Rosenfeld and Ulbrich (2003), the increase of D_0 and μ , and the decrease of N_0 value from the leading edge to the convective center are results of the coalescence and evaporation process. However the coalescence process is probably dominant from convective center to leading edge, since the number density of large drops in the convective center is increased compared with the leading edge. Also, according to the transition from convective center to trailing edge (increase of μ value and decrease of

number density in small and large drops), it is considered that the coalescence and break-up process are combined.

At the time the graupel appeared in the convective and stratiform region, as mentioned in Subsection 3.3, the shape of the RDSD became a more upward convex shape and the averaged RDSD parameters are changed as follows: the value of D_0 and μ increase and the N_0 decrease compared to previous time. This could be due to the difference in the graupel-raindrop and raindrop-raindrop collision efficiencies and the coalescence process probably enhanced by the graupel, which is a relatively large particle, although this hypothesis needs further investigation.

4.2 Comparison with other maritime storms

Histograms of gamma RDSD parameters for the convective center, convective edges (including leading edge and trailing edge), and stratiform region are shown in Fig. 11. The D_m values for the stratiform region show well defined peaks at 1.8 mm with a 2.0 mm distribution breadth. A D_m value with high frequency (modal value) in the convective center is seen at 2.3 mm, which is larger than for the stratiform region, although the size of distribution range is same. However, the convective edge has a broader distribution range of D_m (3.0 mm) with the same modal value of 1.8 mm. The N_W distribution for the convective center and stratiform region is similar to the D_m distribution. Peak values of $\log_{10}N_W$ for the convective center and stratiform region are found at 3.8 and 3.3, respectively. The size of distribution range for the two regions is similar, while the convective center has a higher value of $\log_{10}N_W$. However, the convective edge has a larger modal value of N_W (3.8), which is the same as for the convective center, and a broader distribution range of N_W (2.5). The convective and stratiform regions are distinct from each other in the $D_m - \log_{10}N_W$ scatter plot (Fig. 12). The averaged values of D_m (std. dev.) are 2.24 (0.48), 1.75 (0.31), and 1.70 (0.31) mm and the averaged $\log_{10}N_W$ values (std. dev.) are 3.63 (0.45), 3.55 (0.30), and 3.13 (0.34) $\text{mm}^{-1}\text{m}^{-3}$ for the convective center, convective edge, and stratiform region, respectively. In order to make a comparison with other storms in previous studies, the RDSD data for the convective edge were restricted to rainfall intensities over 5 mm h^{-1} . There is a remarkable tendency for the scattering of $\log_{10}N_W$ to decrease with increasing D_m . The averaged values of $\log_{10}N_W$ versus D_m in the convective center (closed circle with $\pm \sigma$ standard deviation bars), convective edge (open circle with $\pm \sigma$ standard deviation bars), and stratiform region (cross symbol with $\pm \sigma$

Fig. 11. Histograms of D_0 and $\log_{10}N_W$ for convective center (CC), convective edge including leading edge and trailing edge (LT) and stratiform (SS) of maritime squall line system on June 2, 2008 observed in Taiwan.

standard deviation bars) are represented in Fig. 13. The other background data show the statistics of $\log_{10}N_W$ and D_m from different climatic regimes as analyzed by Bringi et al. (2003), in which the radar and disdrometer data were collected from Darwin (Australia), SCMEEX (South China sea Monsoon EXperiment), Papua New Guinea, Florida, Colorado, TOGA-COARE (Tropical Ocean Global Atmosphere - Coupled Ocean-Atmosphere Response Experiment), Arecibo, Graz (Austria), Sydney, and Kwajalein. The methodology for retrieval of N_W and D_0 from S-Pol, CSU-CHILL and Kewajex radar is referred to Bringi et al. (2001), and RSDS parameters were calculated using normalized gamma DSD and the disdrometers to measure the RSDS at a given location are included in Fig. 13. The gray and black marks represent stratiform and convective rain, respectively. The averaged values of $\log_{10}N_W$ and D_m are plotted in the low part of the fitted line for the

stratiform. However, the convective region is plotted between the maritime-cluster and continental-cluster. For the Taiwan squall line system, the stratiform region positioned in the lower part of the fitted line for the stratiform on the right side and the convective edge region located between stratiform and convective region. The Convective center had small $\log_{10}N_W$ and large D_m values compared with maritime storms. This could be due to large drop spectra from the coalescence process enhanced by graupel. The other reason could be due to the climate of Taiwan. Thurai et al. (2010) presented statistics of the RSDS parameters, histograms of $\log_{10}(N_W)$ and D_0 , for convective and stratiform rain types across the pre-monsoon buildup and monsoon regimes in Darwin Australia, which further separated for over land and over ocean regions. They note that the largest differences in D_0 and N_W histograms were found to be for convective rain between

Fig. 12. The $\log_{10}N_w - D_m$ scatter plot for the maritime squall line on June 2, 2008, observed in Taiwan. Cross symbols represent the stratiform region and the convective center ($R > 20 \text{ mmh}^{-1}$) and the convective edge including the leading edge and the trailing edge (LT) over the $R > 5 \text{ mmh}^{-1}$ are shown by closed circles and open circles, respectively. The average value of $\log_{10}N_w$ versus the average D_m , together with their $\pm \sigma$ standard deviation bars, for the convective center, the convective edge and the stratiform region are represented by a closed circle, an open circle and a cross symbol, respectively.

buildup and monsoon regimes (independent of land or ocean areas) and the reason for the independence from land and ocean areas would be the maritime climate of Darwin. Those are just hypothesis and further investigation is needed in order to validate.

Table 4 shows the comparison between RDSD parameters in convective regions for the Taiwan squall line system and other maritime storms observed during TOGA COARE, as analyzed by Ulbrich and Atlas (2007) using the gamma function to represent the RDSD measured by RD-69 (Joss and Waldvogel 1967). When compared with tropical ocean storms, the convective region of the Taiwan squall line system has small values and a narrow range of μ , A , and N_w , but large values and a broad range of D_0 .

5. Summary and conclusion

In the present study we have identified the characteristics of RDSD and microphysical processes in a maritime squall line system. The squall line system was partitioned into 4 regions: the leading edge, convective center, trailing edge, and stratiform. The leading edge, which belongs to the convective line has upward motion from the surface and contains many small

Fig. 13. The average value of $\log_{10}N_w$ versus average D_m , together with their $\pm \sigma$ standard deviation bars plot for convective center, convective edge and stratiform rain. The black and gray color open marks represent convective and stratiform rain, respectively. Open circles (disdrometer) and squares (radar) data are from Bringi et al. (2003). The dotted straight line shows the least squares fitting for stratiform rain. Maritime and continental clusters were classified by Bringi et al. (2003).

drops. The leading edge was characterized by a small D_0 and shape parameter and a linear RDSD shape. In the convective center, a strong updraught rose to the top of the cell with time and many large drops over 4 mm in diameter were observed. The convective center has a large D_0 and N_w parameter, and it is characterized by an upward convex shape. The diameter of raindrops decreased toward the trailing edge, with no updraught or only weak updraughts at high altitudes. The trailing edge was found to have large shape, sloping parameters and a more upward convex shape. The bright band was observed in the stratiform region, with continually downward motion from the bright band to the surface, even though the intensity became weak. D_0 and the N_w parameter were small in the stratiform, and the RDSD had an upward convex shape.

From the leading edge to the convective center, the number of small drops decreased and the number of large drops increased, and then an increased D_0 and μ value, with a decrease in N_0 , were observed. And the trailing edge had an upward convex shape with a very high value of μ . Based on the transition of RDSD parameters and shape, the coalescence process is probably dominant from the leading edge to convective center and the process, which combined the coalescence and break-up, probably occurred from convective

Table 4. Comparison between convective regions of Taiwan squall line and other maritime storms with RDSD parameters. The other maritime storms data are obtained from Ulbrich and Atlas (2007).

Convective region	Maritime storms	Taiwan Squall line
Shape (μ)	3 ~ 15	-0.5 ~ 11.4
Slope (A)	4 ~ 12	2.1 ~ 5.8
Median volume diameter (D_0 , mm)	1.3 ~ 1.7	1.4 ~ 3.2
Normalized intercept parameter (N_W , m^{-4})	2×10^4	7.2×10^3

tive center to trailing edge.

In the convective line, a strong updraught in the upper layer and a strong downdraught from the bottom layer to the surface coincided with the region where graupel occurred. At the same time, very large drop spectra was observed at the surface.

The convective region was found to have large D_0 (D_m), small N_W , and small, narrow ranges of shape (μ) and slope (A) parameters compared with maritime storms. This particular stratiform region, which trailed convective regions, had large D_0 (D_m) and small N_W compared with other stratiforms.

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