The Kinematic and Microphysical Characteristics and Associated Precipitation Efficiency of Subtropical Convection during SoWMEX/TiMREX

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ABSTRACT

Dual-Doppler, polarimetric radar observations and precipitation efficiency (PE) calculations are used to analyze subtropical heavy rainfall events that occurred in southern Taiwan from 14 to 17 June 2008 during the Southwest Monsoon Experiment/Terrain-Influenced Monsoon Rainfall Experiment (SoWMEX/TiMREX) field campaign. Two different periods of distinct precipitation systems with diverse kinematic and microphysical characteristics were investigated: 1) prefrontal squall line (PFSL) and 2) southwesterly monsoon mesoscale convective system (SWMCS). The PFSL was accompanied by a low-level front-to-rear inflow and pronounced vertical wind shear. In contrast, the SWMCS had a low-level southwesterly rear-to-front flow with a uniform vertical wind field. The PFSL (SWMCS) contained high (low) lightning frequency associated with strong (moderate) updrafts and intense graupel–rain/graupel–small hail mixing (more snow and less graupel water content) above the freezing level. It is postulated that the reduced vertical wind shear and enhanced accretional growth of rain by high liquid water content at low levels in the SWMCS helped produce rainfall more efficiently (53.1%). On the contrary, the deeper convection of the PFSL had lower PE (45.0%) associated with the evaporative loss of rain and the upstream transport of liquid water to form larger stratiform regions. By studying these two events, the dependence of PE on the environmental and microphysical factors of subtropical heavy precipitation systems are investigated by observational data for the first time. Overall, the PE of the convective precipitation region (47.9%) from 14 to 17 June is similar to past studies of convective precipitation in tropical regions.

1. Introduction

The development of a precipitation system is mainly supported by water vapor from its environment. A portion of the water vapor returns to the ground as precipitation (e.g., rain) through various microphysical processes (e.g., evaporation, condensation), while the remainder humidifies the atmosphere. These processes are fundamental components of the atmospheric water cycle. Precipitation efficiency (hereafter PE), defined as the ratio of the total rainfall \(R_{\text{tot}}, \text{kg}\) to the total water vapor \(Q_{\text{tot}}, \text{kg}\) ingested into the cloud from the environment (Sui et al. 2005, 2007), is an important parameter resulting from these processes to characterize precipitation systems. In addition, the PE determined by control parameters (e.g., synoptic conditions, microphysical processes) plays an important role in the global water cycle by distributing the water in various forms throughout the entire atmosphere. The variation of control parameters in altering PE and consequent precipitation patterns under climate change (e.g., drought due to reduced PE) is also a key issue for numerous socioeconomic activities (Tegart et al. 1990). A better...
understanding of the control parameters of PE improves numerical weather prediction and reduces the damage from extreme hazards (Doswell et al. 1996).

The kinematic and microphysical structures of precipitation systems are mainly determined by the environmental conditions in different climatological regions. The precipitation systems subsequently evolve diversely with different PEs, which can vary between 10% and 110% (Market et al. 2003). Various factors influencing the PE have been studied via numerical simulations (e.g., Weisman and Klemp 1982; Ferrier et al. 1996; Li et al. 2002; Tao et al. 2004; Sui et al. 2005, 2007). Ferrier et al. (1996) indicate that the vertical tilting of the updraft, which is controlled by vertical wind shear, is important to determine the PE, while the moisture content is responsible for 10% of the PE variation. Murata (2009) found that the enhancement of PE in a heavy rainfall event was attributed to the conversion of cloud water to rainwater via accretion of cloud water by rain.

Observational studies investigated the PE (e.g., Marwitz 1972; Fankhauser 1988; Market et al. 2003; Shusse and Tsuboki 2006; Anip and Market 2007) by using the kinematic fields derived from Doppler radars and moisture fields obtained from rawinsondes. A summary of PE studies is shown in Table 1. Marwitz (1972) found that the enhancement of PE in a heavy rainfall event was attributed to the conversion of cloud water to rainwater via accretion of cloud water by rain. Moreover, most studies of PE focus on precipitation systems in the tropics (Gamache and Houze 1983; Chong and Hauser 1989; Rauber et al. 1996; Simpson et al. 1988) and higher latitudes during the warm season (Fankhauser 1988; Market et al. 2003; Shusse and Tsuboki 2006). The PE of the precipitation systems in the subtropical regions has received little attention.

During the North American Monsoon Experiment (NAME; Higgins et al. 2006), Nesbitt et al. (2008) analyzed subtropical precipitation systems in northwestern Mexico during the onset of the North American monsoon. They hypothesize that the PE of warm rain processes may increase at high elevations due to the low cloud base associated with reduced evaporation compared to low-elevation regions in the Sierra Madre Occidental (SMO). Rowe et al. (2008) concluded that the large vertical distance between the cloud base and the freezing level (4.5 km) along the coastal plain during NAME suggested a greater role for warm rain processes.
compared to higher terrain. Although the PE of subtropical systems during NAME was investigated, it was only in a qualitative sense.

The Southwest Monsoon Experiment/Terrain-Influenced Monsoon Rainfall Experiment (SoWMEX/TiMREX), a joint Taiwan–U.S. field project containing extensive observing facilities, was conducted from 15 May to 30 June 2008 in the northern South China Sea (SCS) and southern Taiwan (Jou et al. 2011). The project aimed at understanding the mechanisms of heavy rainfall precipitation systems during the onset of the southwest monsoon (SWM) as it interacted with the mei-yu front and the complex topography (Central Mountain Range) of Taiwan (Fig. 1). Among various observing facilities, the National Center for Atmospheric Research (NCAR) S-band dual-polarization Doppler radar (S-Pol) provided kinematic measurements and rainfall estimation. S-Pol also significantly reduces the rainfall estimation error from attenuation [e.g., X-band radars in Shusse and Tsuboki (2006)] and hail contamination (Fankhauser 1988). Most importantly, S-Pol polarimetric measurements further help interpret the microphysical characteristics of precipitation systems that were not available for previous observational PE studies. The SoWMEX/TiMREX dataset is ideal to simultaneously study PE and the associated microphysical characteristics of subtropical precipitation systems.

A prefrontal squall line (PFSL) on 14 June and a southwesterly monsoon mesoscale convective system (SWMCS) on 16 June during SoWMEX/TiMREX are investigated in this study. These two systems (meso $a$, 200–2000 km) were under distinct synoptic conditions (Wang et al. 2014a,b) but both systems produced more than 200 mm of accumulated rainfall within 24 h (Fig. 2). The diverse mesoscale characteristics of convection initiation and maintenance of these two precipitation systems have been examined in Davis and Lee (2012) and Xu et al. (2012). Yet, the role of microphysical processes in the precipitation mechanisms and the PEs of these two events have not been examined. Investigating these two heavy precipitation systems helps us to understand the relation of environmental and microphysical characteristics to the PE of subtropical heavy precipitation systems in Taiwan.
The major goals of this paper are to examine the microphysical characteristics and quantify PEs of these two subtropical heavy precipitation systems. Moreover, the dependence of PEs on their environmental and microphysical factors using observational data will be investigated for the first time. The authors first examine the kinematic and microphysical characteristics of these systems under distinct synoptic conditions and, then, investigate the corresponding PEs and their relations to kinematic and microphysical characteristics. The methodology used in this research is presented in section 2. The synoptic conditions, environmental instability, and the spatiotemporal structures of these precipitation systems are reviewed in section 3. Section 4 portrays the mesoscale characteristics and kinematic fields from dual-Doppler analyses. The microphysical characteristics are presented in section 5. The PE is investigated and related to synoptic, thermodynamic, kinematic, and microphysical characteristics in section 6. Finally, a summary is provided in section 7.

2. Methodology

a. Kinematic field retrieval from three-dimensional wind field synthesis

The three-dimensional wind fields were derived from the variational method from Liou and Chang (2009) every 7.5 min across two regions (Fig. 1). The variational method derives the vertical motion via dynamical constraints and numerical smoothing terms including the anelastic continuity equation, vertical vorticity equation, background wind, and spatial smoothness terms. The advantage of this algorithm is that it negates the need to artificially prescribe the top or bottom boundary conditions for the vertical velocities in the traditional sense and estimates more accurate vertical velocities (Mewes and Shapiro 2002), which is essential for PE calculation. The horizontal and vertical resolutions of retrieved wind fields are 1.0 and 0.5 km, respectively, and the top boundary is 15.0 km to cover the tops of the precipitating systems. The available volumes of dual-Doppler analysis are summarized in Table 2.

b. Microphysical retrieval from S-Pol

1) Rain and ice water content estimation

The rain and ice water content was estimated from the S-Pol measurements according to the fuzzy-logic method of particle-type identification (PID; Vivekanandan et al. 1999). In the presence of mixed-phase precipitation (e.g., graupel–rain mixture and rain–hail mixture), the difference reflectivity ($Z_{DP}$, dB) method (Golestani et al. 1989)
was used to discriminate horizontally polarized reflectivity (Z\text{HH}) for rain and ice. The following Z\text{DP}-Z\text{rain} relation was determined from 5 yr of disdrometer data in Taiwan:

\[ Z^{\text{rain}} = 19.43271 + 0.40917Z_{\text{DP}} + 0.00661Z_{\text{DP}}^2. \]  

The estimates of rain mass (M\text{r}, g m\text{–3}) and ice mass (M\text{i}, g m\text{–3}) were derived using the following Z–M relationships:

\[ M_{\text{r}} = 3.44 \times 10^{-3} (Z_{\text{HH}}^{\text{rain}})^{4/7} \]  

and

\[ M_{\text{i}} = 1000\pi\rho_{\text{i}}N_0^{3/7} \left( \frac{5.28 \times 10^{-18} Z_{\text{HH}}}{720} \right). \]  

The Z–M relationships specifically for SoWMEX/TiMREX were not available due to the lack of in situ measurements. Hence, the Z–M relationships were adopted from previous research conducted in subtropical regions (Carey and Rutledge 2000; Cifelli et al. 2002; Wang and Carey 2005). When only ice was identified (e.g., hail, snow, ice), the ice mass was estimated via (3). For rain mass in rain-only categories, the constrain-gamma raindrop size distribution (RSD) retrieval (Zhang et al. 2001; Vivekanandan et al. 2004) was applied to retrieve M\text{r}. The constrain-gamma method can retrieve more accurate RSDs, as its natural variability is obtained by using reflectivity and differential reflectivity (Z\text{DR}, dB) simultaneously.

2) RAINFALL-RATE ESTIMATION

The rainfall estimation was obtained at 2.0-km altitude where the S-Pol had better spatial coverage without partial beam blockage effects (Zhang et al. 2013). A simplified decision-tree logic algorithm combining the K\text{DP}–R and Z–R from S-Pol measurements (Cifelli et al. 2002; Bringi and Chandrasekar 2001) was used in this study. The algorithm is presented in the following form:

\[ R = 54.3K_{\text{DP}}^{0.806} \text{ (mm h}^{-1}\text{) when } Z_{\text{HH}} > 30 \text{ dB and } K_{\text{DP}} > 0.5 \text{ km}^{-1}, \]  

else the following Z–R relation is used,

\[ R = \left( \frac{Z_{\text{HH}}}{338.2} \right)^{1/1.244} \text{ (mm h}^{-1}\text{).} \]  

The coefficients of (4) and (5) were obtained from 5 yr of disdrometer data in Taiwan.

c. Classification of precipitation type

To investigate the characteristics of the PE of convective and stratiform systems, a robust algorithm (Steiner et al. 1995) separating convective and stratiform region was applied. The precipitation types were identified from low-level radar reflectivity (i.e., 2-km height) by examining the spatial uniformity and intensity. The visual examination of the results shows the algorithm separates the convective and stratiform region fairly well.

d. Precipitation efficiency

The PE is defined as the ratio between total rainfall (R\text{tot}) and total water vapor (Q\text{tot}) of a precipitation system:

\[ \text{Precipitation efficiency (PE)} = \frac{R_{\text{tot}}}{Q_{\text{tot}}} \times 100\%. \]  

### Table 2. The total number of available dual-Doppler analysis volumes for the PFSL and SWMCS. The total hours are listed in parentheses. The spatial structure characteristics, vertical wind shear, lightning activity, and instability (S) of the precipitation systems are summarized correspondingly.

<table>
<thead>
<tr>
<th></th>
<th>PFSL: 0000 UTC 14 Jun–2230 UTC 14 Jun</th>
<th>SWMCS: 1930 UTC 15 Jun–1500 UTC 16 Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of 3D wind retrieval volumes</td>
<td>183 (22.87 h)</td>
<td>112 (14.0 h)</td>
</tr>
<tr>
<td>Spatial structure of the precipitation system</td>
<td>Fast-moving squall line associated with northeast–southwest-oriented rainband with trailing stratiform</td>
<td>Nearly stationary MCSs associated with widely separated convective cells</td>
</tr>
<tr>
<td>Vertical wind shear</td>
<td>Pronounced vertical wind speed shear (( u )-component wind shear between 0.5 and 12 km ( \sim 0.684 \text{ m s}^{-1} \text{ km}^{-1} ))</td>
<td>Uniform wind speed profile (( u )-component wind shear between 0.5 and 12 km ( \sim -0.258 \text{ m s}^{-1} \text{ km}^{-1} ))</td>
</tr>
<tr>
<td>Instability (S) (( \partial \theta_e/\partial p ))</td>
<td>6.5 K (100 hPa)(^{-1} )</td>
<td>3.0–4.0 K (100 hPa)(^{-1} )</td>
</tr>
<tr>
<td>Lightning activity</td>
<td>High-frequency, max lightning frequency ( \sim 0.2 \text{ h}^{-1} \text{ (10 km)}^{-2} )</td>
<td>Low-frequency, max lightning frequency ( \sim 0.2 \text{ h}^{-1} \text{ (10 km)}^{-2} )</td>
</tr>
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</table>
The $R_{\text{tot}}$ was derived by integrating the estimated rainfall rate ($R$, mm h$^{-1}$) from (4) and (5) over a specified area ($dA_k$, e.g., stratiform or convective region) and a time window ($dt$) as follows:

\[ R_{\text{tot}} = \rho_w \int_{T} \int_{A_k} R \, dA_k \, dt, \quad (7) \]

where $\rho_w$ is the density of rain (g m$^{-3}$). Doswell et al. (1996) suggested defining a volume around the system of interest and employing winds that facilitate influx and precipitation calculations for determining PE. The size of the precipitation systems usually exceeded the dual-Doppler analysis region; therefore, the $Q_{\text{tot}}$ was derived consequently from both bottom and lateral boundaries of the precipitation system:

\[ Q_{\text{tot}} = \rho_a^2 \int_{A_k} w^2 \, dA_k \, dt + \int_{T} \int_{A_k} -\rho_a q_v^h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \, dA_k \, dz \, dt. \quad (8) \]

3. Environmental conditions and evolution of the precipitation systems

The environmental conditions and evolution of the precipitation systems have been documented in previous research (Davis and Lee 2012; Xu et al. 2012; Wang et al. 2014a,b). A brief summary is provided in this section.

a. Synoptic conditions

Between 14 and 17 June 2008, Taiwan was in a prefrontal environment, while the mei-yu front extended east-northeast (southeast of Japan) to west-southwest (southeast of the China coast) and remained to the north of Taiwan (Wang et al. 2014a,b). Cyclonic wind shear was located over eastern China (Figs. 3a–c) associated with the mei-yu front on 14 June and weakened on 15 June.

As shown in Figs. 3a, b; 3d, e; and 3g, h, the southwesterly low-level jet (LLJ) from 800 to 700 hPa flowed around the region near the north SCS and southwest Taiwan from 14 to 16 June (Wang et al. 2014a,b). The time–height cross section of the wind fields from Ping-Dong station (Fig. 4) shows the wind intensified around 0000 UTC 14 June from 850 to 600 hPa as the PFSL passed by. The low-level (900–600 hPa) winds were mainly southwesterly with westerly winds above 400 hPa during the PFSL passage. The high wind speed ($>10$ m s$^{-1}$) that accompanied the PFSL passage was observed throughout most of the troposphere (900–100 hPa). The PFSL fully passed southern Taiwan at 2230 UTC, the wind speed then decreased, and the wind direction had a more southerly component.

During SWMCS, the southwesterly wind was restored at 2100 UTC 15 June (Fig. 4) as the MCS associated with SWM developed near southern Taiwan from the north SCS. The low-level warm, moist, and unstable air was found over the north SCS on 16 June (Xu et al. 2012;
FIG. 3. The mixing ratio of water vapor (g kg$^{-1}$), wind fields (m s$^{-1}$), and geopotential height (m) at 800, 700, and 500 hPa from the National Centers for Environmental Prediction’s (NCEP) Final (FNL) operational global analysis data at 0000 UTC 14–17 Jun are shown as shaded colors, vectors, and contours, respectively. The reference wind vectors (10 m s$^{-1}$) are shown at lower-right corner.
Wang et al. 2014a). The SWMCS had a uniform wind speed profile. The wind direction turned southerly at 1200 UTC 16 June (Fig. 4) as part of the circulation of the Pacific subtropical high located over eastern Taiwan (Figs. 3j–l). While the Pacific subtropical high gradually extended westward (5880-m contour at 500 hPa in Figs. 3c,f,i,l), the moist air over southern Taiwan shifted northward around 1200 UTC 16 June (not shown) and the air mass over southern Taiwan became relatively drier (Ruppert et al. 2013). The MCS subsequently decayed due to the relatively dry air (Chen et al. 2007).

The low-level moisture field suggests that southern Taiwan remained moist (mixing ratio of water vapor at 800 hPa $>12$ g m$^{-3}$; Figs. 3a,d,g,j). The relative humidity remained high (>70%) from the low to upper levels (1000–300 hPa) during 14–17 June (Fig. 4). This high relative humidity provided a favorable environment for efficient rainfall production by preventing the loss of raindrops from evaporation (Rauber et al. 1996).

b. Environmental instability

The environmental instability $S$ is defined as the vertical gradients of equivalent potential temperature ($\frac{\partial \theta_e}{\partial p}$) from the surface (1000 hPa) to midlevel (600 hPa), as shown in units of K (100 hPa)$^{-1}$ (positive values indicate a decrease in $\theta_e$ with height) in Fig. 5. The environment was very unstable on 13 June with $S$ of $\sim$6.5 K (100 hPa)$^{-1}$, but gradually stabilized from north to south as the PFSL propagated southeastward. After the PFSL passed the Ma-Kung and South Ship stations at 1800 UTC 13 June and 0600 UTC 14 June, $S$ gradually stabilized to $\sim$2.0 K (100 hPa)$^{-1}$. The post-PFSL environment remained low $S$ [$\sim$2.0 K (100 hPa)$^{-1}$] from 0000 to 0900 UTC 15 June. The environment over the north SCS (South Ship) began to destabilize again at 1200 UTC 15 June [$\sim$3–4 K (100 hPa)$^{-1}$] as the SWM extended northeasterly. It is also noteworthy that the instability of southern Taiwan during the SWM intensification period was less unstable [3–4 K (100 hPa)$^{-1}$] compared to the pre-PFSL environment [6.5 K (100 hPa)$^{-1}$].

c. Spatiotemporal evolution of the precipitation systems

The synoptic conditions of 14 and 16 June had pronounced differences, and consequently, the precipitation systems had dissimilar spatiotemporal evolutions. A northeast–southwest-oriented PFSL triggered by the mei-yu front developed over the southeast China coast on late 13 June. Satellite IR images show that the PFSL propagated southeasterly toward Taiwan on 14 June.
(Fig. 6a). The PFSL was subsequently altered by the complex terrain (Figs. 6b,c). The northern part of the PFSL became less organized and the southern part changed to an east–west orientation. The entire PFSL passed through Taiwan at 2230 UTC 14 June (Fig. 6d). After the PFSL passage, scattered precipitation from the northern SCS associated with the SWM propagated northeastward into southwest Taiwan (Figs. 6e,f). The

![Fig. 5. Time series of the environmental instability $S$ is defined by the vertical gradients of equivalent potential temperature $[\partial \theta_e/\partial p]$, in K (100 hPa)$^{-1}$ from the surface (1000 hPa) to midlevels (600 hPa) at the Ma-Kung and South Ship sounding stations shown as solid and dashed lines, respectively.](image)

![Fig. 6. The brightness temperature (K) from the Magyar Satellite-1 (MASAT-1) IR channel over East Asia every 6 h from (a) 0030 UTC 14 Jun to (l) 1830 UTC 16 Jun. The prefrontal squall line on 14 Jun is marked as a dashed line in (a). The MCS on 16 Jun is marked as a dashed circle in (i).](image)
system gradually weakened around 0900 UTC 15 June and was followed by a break with less intense convection (Figs. 6g,h).

Another intense precipitation system approached the southwest coast of Taiwan around 1930 UTC 15 June as it moved from the north SCS toward the northeast (Fig. 6i). The SWMCS (Figs. 6i,j) developed offshore and remained quasi stationary over the upstream ocean and southwest coast of Taiwan (Xu et al. 2012). The precipitation system later transformed to scattered convective cells at 1200 UTC 16 June (Figs. 6k,l).

4. Kinematic characteristics

The aforementioned evolving synoptic conditions between 14 and 16 June resulted in distinct spatiotemporal structures in PFSL and SWMCS (summarized in Table 2). Considering the organizational/structural modes were different in PFSL and SWMCS, only the data from available dual-Doppler analysis periods were included for the investigation to ensure the consistency of kinematic, microphysical, and PE analyses. The horizontal winds (no vertical velocity) at 2.5 km were obtained by a conventional approach (Armijo 1969; Miller and Strauch 1974) from three radar (RCCG, RCKT, and S-Pol) syntheses (Fig. 7) to better illustrate the general flow patterns of these two events. The detailed kinematic structures of these two systems are portrayed using radar reflectivity and variational-derived system-relative wind analyses in the dual-Doppler analysis areas (black boxes in Fig. 7).

a. Prefrontal squall line

The S-Pol mosaic reflectivity at 1000 UTC 14 June (Fig. 7a) illustrates that the PFSL was composed of several northeast–southwest-oriented rainbands associated with both convective and stratiform precipitation. The individual convective cells moved from the southwest to the northeast while the synoptic low-level flow was southwesterly (Fig. 7a). The detailed kinematic structures are illustrated by the reflectivity and system-relative wind fields as shown in Fig. 8.1 As the rainband moved toward the southeast, the low-level front-to-rear flow was observed along the eastern side of the rainband with northeasterly system-relative winds at 2 km (Fig. 8a). The low-level front-to-rear flow decelerated toward the leading edge of the rainband. A midlevel rear-to-front flow with westerly winds was found on the western side of the rain band at 5 km (Fig. 8b).

The vertical cross sections of reflectivity and divergence overlaid by the system-relative wind field of the most vigorous cell (i.e., most intense vertical velocity) at $y = -14$ km (A–B in Fig. 8) are shown in Fig. 9. The convective precipitation represented by the intense reflectivity field at $x = -60$ km was accompanied by a relatively strong updraft (maximum retrieved updraft $\sim 10.0$ m s$^{-1}$) located at $-7$ km altitude in the convective core (Fig. 9a). The convergence field of the convective region can be found up to 6 km (Fig. 9b). The low-level front-to-rear flow transported moist and unstable pre-squall-line air into the convective cells (Fig. 9b). The updraft further transported the water vapor deeper into the upper levels of the troposphere. The midlevel rear-to-front flow with system-relative wind speed of about 4.0 m s$^{-1}$ is observed at 6.0 km (Fig. 9b).

Unlike the tropical convection often associated with maximum low-level convergence and an updraft in a narrow ribbon within 1–2 km of the leading edge (LeMone et al. 1984, 1998; Jorgensen et al. 1997), the convective system in this case (at $x = -60$ km in Fig. 9a) was located about 15 km behind the leading edge (reflectivity = 0 dB, $x = -45$ km in Fig. 9a). This feature is similar to a squall line in the SCS described by Wang and Carey (2005). The trailing stratiform region ($x = -90$ to $-75$ km) with a pronounced bright band was located behind the convective region with a transition region ($x = -75$ to $-65$ km) between them. The transition region was characterized by weaker reflectivity without a bright band. The upper-level (>7.0 km) westerly flow ahead of the convective line transported particles downstream, forming a pre-squall-line stratiform region. As the PFSL formed over southeast China and propagated toward Taiwan, the kinematic structure of the evolving PFSL was similar to the midlatitude squall line summarized in Houze (1993).

b. Southwesterly monsoon mesoscale convective system

Convective characteristics in SWMCS at 0507 UTC 16 June (Fig. 7b) were distinctly different from those in the PFSL portrayed in Fig. 7a. The SWMCS was composed of scattered cells generated repeatedly offshore that moved onshore (Xu et al. 2012; Wang et al. 2014a,b). These cells were at the convergence zone of westerly winds at the northwest part of the SWMCS and southwesterly flow upstream. This westerly wind was part of a disturbance over the coastal area in southern China and can be seen up to 3 km from the Ma-Kung sounding (not shown). The MCS gradually weakened and dissipated at 0600 UTC 16 June while the westerly winds

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1 The system-relative wind fields were obtained by subtracting the system motions that were determined by examining two consecutive scans of convective cells. The motions of the PFSL were about 10.3 and 12.0 m s$^{-1}$ in the $x$ and $y$ directions, respectively. The system motion derived in this research is considered to be the motion of convective cells.
FIG. 7. (a) The mosaic reflectivity at 1000 UTC 14 Jun from S-Pol. The vectors represent winds at 2.5 km derived from three radar syntheses (RCCG, RCKT, and S-Pol). The box represents the dual-Doppler analysis region of RCCG–S-Pol. The topography of 0.5 km is shown as a black contour line. (b) As in (a), but at 0507 UTC 16 Jun. The box represents the dual-Doppler analysis area of RCKT–S-Pol.
slowly withdrew toward the north and were replaced with predominant southerly winds from the Pacific subtropical high over southern Taiwan.

An intense southerly to southwesterly low-level rear-to-front flow was found in the SWMCS (Fig. 10a). The low-level rear-to-front flow provided continuous moist and unstable air from the north SCS to support the quasi-stationary MCS. The north–south-oriented convective line was located at $x = 52 \pm 50$ km. The convergence of the wind field in the convective cell can be clearly seen from low to midlevels (2–5 km; Fig. 10b).

The depth of the low-level rear-to-front flow (with $u$-component wind speed of about 2.0–6.0 m s$^{-1}$) was about 4.0 km (Fig. 11a), much deeper than the low-level front-to-rear inflow in PFSL. This convective cell was less intense and less elevated compared to the PFSL in terms of reflectivity. The corresponding convergence field was also less elevated (up to 5 km) compared to PFSL (Fig. 11b). Uniform easterly winds above 6 km carried the particles upstream and formed stratiform precipitation.

c. Composite vertical structure of kinematic fields

The kinematic fields of PFSL and SWMCS have been characterized by the analysis of representative dual-Doppler analysis and show distinct features. To examine the general features of the kinematic fields statistically, the contoured frequency by altitude diagram (CFAD; Yuter and Houze 1995) was applied. The CFADs of horizontal velocity, upward motion, and divergence fields of convection including all available dual-Doppler analysis periods are shown in Fig. 12. Because of the higher westerly wind speed between 900 and 400 hPa during the PFSL period (Fig. 4), the PFSL (Fig. 12a) had stronger $u$-component winds than did the SWMCS (Fig. 12b). Below 2 km, the SWMCS had a stronger $u$ than $u$ component of horizontal velocity consistent with sounding data (Fig. 4). The mean $u$ component of horizontal
velocity (Fig. 12c) shows that the PFSL had pronounced vertical wind shear, while the SWMCS exhibited more uniform profiles. The vertical wind shears from the mean $u$ component of the horizontal velocity between 0.5 and 12 km were 0.684 and $0.258 \text{ m s}^{-1} \text{ km}^{-1}$ for PFSL and SWMCS periods, respectively. In the meantime, the $v$ components show more uniform vertical profiles.

As the pronounced vertical wind shear supported deep convection by separating the updraft and downdraft (Emanuel 1994), as well as a higher environmental instability (Fig. 6), the maximum up- and downdrafts during the PFSL (Fig. 12d, 0.01% contour line) were consequently stronger than those of the SWMCS (Fig. 12e). The divergence field of the PFSL (Fig. 12g) shows larger variances than the SWMCS (Fig. 12h), consistent with stronger up- and downdrafts. Shallower mean convergence fields of SWMCS (Fig. 12i) are consistent with weaker updrafts. Contrary to the SWMCS, the PFSL had a deeper mean convergence (up to 6 km); therefore, the altitude of maximum mean updraft of the PFSL was higher than the SWMCS.

5. Microphysical characteristics

a. Polarimetric measurements

The corresponding S-Pol polarimetric measurements of Figs. 9 and 11 associated with the most intensive convective cells were investigated to illustrate the microphysical characteristics of PFSL and SWMCS. The convection within the PFSL was characterized by strong $Z_{HH}$ ($\sim 50$ dB) associated with a column of high values of differential reflectivity ($Z_{DR} > 1.5$ dB) and specific differential phase shift ($K_{DP} > 2.2^\circ \text{ km}^{-1}$) at about $x = -60$ km in Figs. 13a,b. Note that $Z_{DR}$ provides information about the oblateness of particles and $K_{DP}$ depends on liquid water content (Bringi and Chandrasekar 2001). Therefore, the positive $Z_{DR}$ and $K_{DP}$ column suggests a rain mass existed up to 7-km altitude, well above the freezing level (about 4.7 km according to rawinsonde data). Relatively high values of $Z_{DR}$ (1.5–1.75 dB) and linear depolarization ratio (LDR, $-22$ to $-24$ dB; Fig. 13c) associated with lower values of zero-lag cross-correlation coefficient ($\rho_{HV}, 0.96–0.97$; Fig. 13d) at the freezing level corresponded to the presence of a rain–ice mixture (e.g., melting aggregates). Both LDR and $\rho_{HV}$ help discriminate pure rain ($LDR \leq -30$; $\rho_{HV} = 0.99$) and mixtures of rain and ice. The stratiform precipitation was characterized by a brightband signature of low $\rho_{HV}$ (<0.97) and high $Z_{HH}$, $Z_{DR}$, and LDR (>−24 dB). On the other hand, the SWMCS shows slightly dissimilar features of the polarimetric measurements to the PFSL. The weaker and shallower convection in SWMCS had lower $Z_{HH}$ (blue contour lines in Fig. 13). The rain mass was elevated to the midlevels as $K_{DP}$ columns (Fig. 13f) extended to about 6 km. The higher LDR ($-20$ to $-18$ dB; Fig. 13g) and lower $\rho_{HV}$
(0.94–0.95; Fig. 13h) in the convective region suggest irregular snow mixed with rain.

The distinct microphysical characteristics between the PFSL and SWMCS convective regions were further illustrated by PIDs in Fig. 14. Within the PFSL, the graupel–rain category was located above the melting level and graupel–small hail mixtures were evident at higher altitudes (Fig. 14a). These microphysical features
FIG. 12. (a),(b) The CFAD of the $u$ component of the horizontal wind ($U$, m s$^{-1}$) of convective regions for PFSL and SWMCS periods. The CFAD contours are shaded at 0.01%, 0.1%, 1%, 5%, and 10%. The corresponding mean values of the vertical profiles of the $U$ (solid line) and $V$ (dashed line) components of the horizontal wind of the convective regions are shown in (c). (d),(e) As in (a),(b), but for the updraft ($W$, m s$^{-1}$). (f) The mean values of the updraft (m s$^{-1}$). (g),(h) As in (a),(b), but for the divergence field (DIV, s$^{-1}$). (i) The mean values of DIV.
were similar to the Amazon squall line that formed in low-level easterly flow (Cifelli et al. 2002) and deep convection that initiated over the SMO during NAME (Rowe et al. 2011). During the SWMCS, most of the mixed phases near the melting level were wet snow (Fig. 14b). Only limited graupel and rain–graupel mixtures were found in SWMCS. The SWMCS was similar to the convection during the onset of the SCS monsoon from SCSMEX (Wang and Carey 2005), MCSs that formed in the Amazon within the low-level westerly flow regime (Cifelli et al. 2002) and the organized convections over the Gulf of California and had longer residence over water during NAME (Rowe et al. 2012). The warm rain processes play a more significant role...

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**Fig. 13.** Vertical cross section at 1000 UTC 14 Jun of S-Pol polarimetric measurements of (a) differential reflectivity ($Z_{DR}$), (b) specific differential phase ($K_{DP}$), (c) LDR, and (d) correlation coefficient ($\rho_{HV}$). The system-relative wind and vertical velocity are shown as black vectors and contours, respectively. The 10 m s$^{-1}$ reference vectors are shown in the top-right corner. The blue lines are contours of 30-, 40-, and 50-dBZ reflectivity. The black dashed line represents the 0°C level (4.7 km) according to sounding data. (e)–(h) As in (a)–(d), but at 0507 UTC 16 Jun and the 0°C level is 5.0 km.
than the mixed-phased processes. In the stratiform regions of both the PFSL and SWMCS, the PIDs identified wet snow in the bright band due to water-coated snow or coexisting rain and snow.

b. Composite vertical structure of polarimetric measurements

As the convective (stratiform) regions of PFSL and SWMCS show distinct (similar) features, only the microphysical characteristics of the convective regions are described using CFADs of $Z_{HH}$, $Z_{DR}$, and $K_{DP}$. The PFSL with more intense, deeper convection had 1% of 30-dB $Z_{HH}$ up to 8 km (Fig. 15a). The less intense, shallower convection during the SWMCS periods had 1% of 30-dB $Z_{HH}$ extending through 7 km (Fig. 15b). The mean $Z_{HH}$ profile (Fig. 15c) indicates higher values in PFSL than SWMCS throughout the low to upper levels. Above the freezing level ($h \approx 4.7–5.0$ km), the majority of $Z_{DR}$ values were in the range between 0.0 and 1.0 dB for PFSL and SWMCS (Figs. 15d,e). The downward increase of $Z_{DR}$ due to the melting of wet-snow/graupel was pronounced near the freezing level in both systems. Below the freezing level ($h < 4.0$ km), the 1% frequency of $Z_{DR}$ was toward higher values in PFSL, suggesting larger raindrops. Also, the mean values of $Z_{DR}$ (Fig. 15f) below the freezing level show different slopes ($\text{dB km}^{-1}$) between 0.5 and 3.5 km. They were about $-0.032$ and $0.002$ for PFSL and SWMCS, respectively.

Furthermore, the mass-weighted diameter ($D_m$, mm), defined as

$$D_m = \frac{\int D^4 N(D) dD}{\int D^3 N(D) dD},$$

was obtained to interpret the RSD as function of altitude. The terms $D$ and $N(D)$ represent the raindrop size (mm) and raindrop size distribution ($\text{mm}^{-1} \text{m}^{-3}$). The term $D_m$ was estimated as follows (Bringi and Chandrasekar 2001):

![Figure 14](image-url)
The $Z_{DR}$ is in dB scale from S-Pol. The corresponding slopes (between 0.5 and 3.5 km) of $D_m$ in the convective regions were $-0.029$ for PFSL and 0.002 (mm km$^{-1}$) for SWMCS. The downward increase of mean values of $Z_{DR}$ ($D_m$) for the PFSL suggests that the relatively larger raindrops caused by melting graupel further increased in size by collecting other raindrops via the collision-coalescence process during its fall to the surface in the

$$D_m = 1.619(Z_{DR})^{0.485} \text{.}$$

(10)
convective regions. On the other hand, mean $\text{Z}_{\text{DR}}$ ($D_m$) of the SWMCS remained constant with altitude as the raindrops formed by the melting of wet snow.

The $K_{\text{DP}}$ of PFSL and SWMCS (Figs. 15g,h) remained low ($0.08-0.58 \text{ km}^2 \text{g}^{-1}$) above the freezing level, indicating limited rainwater content. The 1% frequency of $1.08 \text{ km}^2 \text{g}^{-1}$ $K_{\text{DP}}$ can be found at 3.0 km during PFSL, but only at 1.8 km during SWMCS, suggesting that the stronger updraft in PFSL could carry liquid water to a deeper level. It is noticed that the SWMCS had higher values of mean $K_{\text{DP}}$ above 8 km (Figs. 15f,i). It is postulated that the lower (higher) values of mean $Z_{\text{DR}}$ and $K_{\text{DP}}$ from PFSL (SWMCS) were due to more irregular ice crystals (oriented ice crystals) according to PIDs (not shown).

The mean $K_{\text{DP}}$ (Fig. 15i) between 3 km and the freezing level was greater for PFSL than SWMCS, suggesting more liquid water present in the midlevels for PFSL. It is noticed that the higher slope of mean $K_{\text{DP}}$ (between 0.5 and 3.5 km) in SWMCS ($-0.053 \text{ km}^{-1}$) than in PFSL ($-0.036 \text{ km}^{-1}$) suggests that the rainwater content also increased downward at a greater rate in the SWMCS. Hence, the SWMCS had higher mean $K_{\text{DP}}$ below 2 km, indicating more rainwater content than PFSL. The low lifting condensation levels (LCLs) during 14–16 June (about 100 m) and the high freezing level (4.7–5.0 km), resulting in deep warm cloud depths of about 4.6–4.9 km, allows for accretional processes to produce rainwater at low levels efficiently, which would explain the increasing $K_{\text{DP}}$ values toward cloud base. Similar results are also found in Rowe et al. (2012).

c. Vertical structural of water content

The vertical profiles of mean liquid water content of rain (LWC) and ice water contents (IWC) of graupel, snow, and ice in convective regions of PFSL and SWMCS, estimated from S-Pol, are summarized in Fig. 16. With stronger updrafts, the graupel IWC of PFSL was a factor of 3 higher than SWMCS (Fig. 16a). The snow IWC in the PFSL above 7 km was slightly higher than in the SWMCS (Fig. 16b) as well. On the other hand, the SWMCS had more wet snow near the freezing level (Fig. 16b) and heavy aggregation of snow above than did the PFSL. In terms of LWC, greater LWC in the SWMCS below 2 km (Fig. 16c) was consistent with observations of higher $Z_{\text{HH}}$ and $K_{\text{DP}}$ with lower $Z_{\text{DR}}$.

d. Lightning data analysis

Greater IWC of graupel and snow with stronger updrafts in convective precipitation systems of the PFSL is found to be associated with higher lightning frequency than SWMCS, as shown in Fig. 17 (summarized in Table 2). Deierling et al. (2008) indicated that particle collision of graupel and ice crystals within the updraft associated with gravitational forces led to separating charges and an increase in the occurrence of lightning flashes. Contrarily, less graupel and weaker updrafts during the SWMCS corresponded to low lightning frequency.

6. Precipitation efficiency

The analyses of synoptic conditions and kinematic and microphysical features from the PFSL and the SWMCS have shown diverse characteristics. The corresponding $R_{\text{tot}}$, $Q_{\text{tot}}$, and PEs were computed in this section to understand the dependence of PE on environmental and microphysical factors. As shown in Fig. 18, the $R_{\text{tot}}$ and $Q_{\text{tot}}$ of convective precipitation regions could vary by a factor of 3 every 7.5 min. The instantaneous PEs (i.e.,

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3 The lightning data were collected by the Taiwan Power Company. The data include the in-cloud (IC) and cloud-to-ground (CG) lightning.
the ratios between $R_{\text{tot}}$ and $Q_{\text{tot}}$ of PFSL and SWMCS range from 30% to 80%, and the variations are presumably due mainly to including different life stages of precipitation systems from radar observations in analysis domains (Doswell et al. 1996). Market et al. (2003) suggest that $R_{\text{tot}}, Q_{\text{tot}},$ and PE are most meaningful when averaged over the lifetime of a system. Subsequently, the PE, mean total rainfall flux ($R_{\text{tot},k} \text{ kg km}^{-2} \text{s}^{-1}$), and the water vapor flux ($Q_{\text{tot},k} \text{ kg km}^{-2} \text{s}^{-1}$) from (6)–(8) were calculated for the entire PFSL, SWMCS, and 14–16 June (ALL). The “bulk” PE including all life stages is referred to in the following discussion.

As summarized in Table 3, the convective region in SWMCS had higher $R_{\text{tot}}$ (3509.2 kg km$^{-2}$ s$^{-1}$) than in PFSL (3176.1 kg km$^{-2}$ s$^{-1}$). This is consistent with higher LWCs of rain in the low levels in SWMCS. The similar contributions of total precipitation from the stratiform (convective) region from PFSL and SWMCS were about 11.5%–15.4% (88.5%–84.6%). Overall, from 14 to 16 June (ALL), stratiform (convective) precipitation contributed about 16.3% (83.7%) of the total precipitation. The coverage partition of stratiform precipitation (67.3%) is consistent with Tropical Rainfall Measuring Mission (TRMM) field studies (Tokay et al. 2001) in the tropics (63%–70%), but much higher than those of Wang and Carey (2005) during SCSMEX (10%–15%). Wang and Carey (2005) hypothesized that the weak vertical velocity and buoyancy limited the generation of the stratiform region with a dry layer in the mid- to upper levels over 500 hPa during SCSMEX.

In terms of the $Q_{\text{tot}}$ in convective regions, the PFSL value (7056.3 kg km$^{-2}$ s$^{-1}$) was higher than that for SWMCS (6607.6 kg km$^{-2}$ s$^{-1}$). The values of $Q_{\text{tot}}$ in the stratiform regions (2271.6 and 2275.0 kg km$^{-2}$ s$^{-1}$, respectively) were about a factor of 2–3 less than those in

Fig. 17. The lightning frequency [h$^{-1}$ (10 km)$^{-2}$] from the north and south dual-Doppler synthesis areas (Fig. 1). The size of the dual-Doppler synthesis area is 15 488 km$^{2}$.

Fig. 18. The total rainfall flux ($R_{\text{tot},k} \text{ kg km}^{-2} \text{s}^{-1}$) and total water vapor flux ($Q_{\text{tot},k} \text{ kg km}^{-2} \text{s}^{-1}$) from cloud base (2.0 km) for every 7.5 min of available dual-synthesis data of precipitation regions with areas greater than 1000 km$^{2}$. The black and gray dots represent the data from PFSL and SWMCS, respectively. The dashed lines represent precipitation efficiency from 30% to 80%.
Table 3. The mean total rainfall flux ($\mathcal{R}_{\text{tot}}$, kg km$^{-2}$ s$^{-1}$) and water vapor flux ($\mathcal{V}_{\text{tot}}$, kg km$^{-2}$ s$^{-1}$) from north and south dual-Doppler analysis areas for convective (con.), stratiform (str.), and entire (overall) precipitation systems (including convective and stratiform) of PFSL, SWMCS, and the entire period from 14 to 16 Jun (ALL) are listed. The corresponding fractions of rainfall flux and water vapor flux from stratiform and convective regions are shown as percentages. The PEs are derived for convective, stratiform, and overall precipitation of PFSL, SWMCS, and the entire period from 14 to 16 Jun as well.

<table>
<thead>
<tr>
<th></th>
<th>Coverage fraction (%)</th>
<th>$\mathcal{R}_{\text{tot}}$ (kg km$^{-2}$ s$^{-1}$)</th>
<th>Precipitation fraction (%)</th>
<th>$\mathcal{V}_{\text{tot}}$ (kg km$^{-2}$ s$^{-1}$)</th>
<th>Vapor flux fraction (%)</th>
<th>PE (%)</th>
</tr>
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<tr>
<td>PFSL, 0000–2230 UTC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Con. 14 Jun</td>
<td>33.3</td>
<td>3176.1</td>
<td>88.5</td>
<td>7056.3</td>
<td>50.9</td>
<td>45.0</td>
</tr>
<tr>
<td>Str. 14 Jun</td>
<td>66.7</td>
<td>2053.3</td>
<td>11.5</td>
<td>2271.6</td>
<td>49.1</td>
<td>9.0</td>
</tr>
<tr>
<td>Overall 14 Jun</td>
<td>—</td>
<td>1193.7</td>
<td>—</td>
<td>3863.5</td>
<td>—</td>
<td>30.9</td>
</tr>
<tr>
<td>SWMCS, 1930 UTC</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Con. 15 Jun–1500 UTC</td>
<td>42.7</td>
<td>3509.2</td>
<td>84.6</td>
<td>6607.6</td>
<td>63.4</td>
<td>53.1</td>
</tr>
<tr>
<td>Str. 15 Jun–1500 UTC</td>
<td>57.3</td>
<td>475.8</td>
<td>15.4</td>
<td>2275.0</td>
<td>36.6</td>
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<tr>
<td>Overall 15 Jun</td>
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<td>—</td>
<td>4123.9</td>
<td>—</td>
<td>42.9</td>
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<tr>
<td>ALL 16 Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Con. 16 Jun</td>
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<td>2909.3</td>
<td>83.7</td>
<td>6078.2</td>
<td>51.6</td>
<td>47.9</td>
</tr>
<tr>
<td>Str. 16 Jun</td>
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<td>276.3</td>
<td>16.3</td>
<td>2176.4</td>
<td>48.4</td>
<td>12.7</td>
</tr>
<tr>
<td>Overall 16 Jun</td>
<td>—</td>
<td>1137.9</td>
<td>—</td>
<td>3453.1</td>
<td>—</td>
<td>33.0</td>
</tr>
</tbody>
</table>

In terms of the PE in convective precipitation, SWMCS (53.1%) was higher than PFSL (45.0%). Despite lower $\mathcal{Q}_{\text{tot}}$ in the convective regions of SWMCS compared to PFSL, the SWMCS could produce more rainfall with higher efficiency. Three possible reasons are identified in this study. First, it is presumed that the higher concentration of raindrops with smaller mean drop size and higher liquid water content at low-levels enhancing the accretional growth of rain (Khairoutdinov and Kogan 2000) improved the PE of the SWMCS. A similar assumption is also found in Murata (2009). Second, the deeper convection with evaporative loss of rain from northern and southern dual-Doppler analysis areas for convective and stratiform regions (e.g., 45%–59% in Table 1). However, the overall PE (ALL) including both convective and stratiform precipitation was 33.0% and higher than the study in eastern China [less than 10% in Shusse and Tsuboki (2006), Table 1]. A strong positive correlation between the PE and the size of the precipitation systems was found in Fankhauser (1988) and Shusse and Tsuboki (2006). The dilution rate of the air within the clouds by entrainment is generally inversely proportional to the size of the clouds. The moist environment (relative humidity >70%) reduced the effect of the entrainment of dry air, and the larger size (10$^3$ km$^2$) of the precipitation systems with lower dilution rates act to increase the PE of the precipitation systems from 14 to 16 June compared to Shusse and Tsuboki (2006) with a drier environment (relative humidity ~70%) and a smaller-sized (10$^2$ km$^2$) precipitation system.

7. Summary

Two diverse subtropical heavy precipitation systems 1) prefrontal squall line (PFSL) and 2) southwesterly monsoon mesoscale convective system (SWMCS) under distinct synoptic conditions from 14 to 16 June during SoWMEX/TiMREX in 2008 over southern Taiwan were investigated. The PFSL was triggered by the mei-yu front over east China in an unstable environment [$S \approx 6.5$ K (100 hPa)$^{-1}$], propagated south-easterly toward Taiwan on 14 June, and featured a northeast–southwest-oriented rainband. Conversely, the quasi-stationary SWMCS developed over the coastal area of southern Taiwan on 16 June and was maintained by a less unstable SWM [$S \approx 3$–4 K (100 hPa)$^{-1}$] from the north SCS.

For the first time, the PE of subtropical precipitation systems is investigated by observational data according to these two events. The PE of the convective precipitation region (47.9%) from 14 to 16 June was similar to the findings of past studies of convective precipitation in tropical regions (e.g., 45%–59%). However, the PE of these entire precipitation systems (33%) was much lower than lower...
higher than the cumulonimbus clouds (10%) in eastern China (Shusse and Tsuboki 2006). It is postulated that the reduced effect of the entrainment of dry air due to the relatively larger size of the precipitation systems and moister environment during 14–16 June increased the PE.

Furthermore, the dependences of PE of subtropical precipitation systems on environmental and microphysical factors were investigated simultaneously via observational data by examining these two events in detail for the first time. Despite the SWMCS having lower \( \overline{Q}_{\text{tot}} \) (6607.6 kg km\(^{-2}\)s\(^{-1}\)) than PFSL (7056.3 kg km\(^{-2}\)s\(^{-1}\)) in convective regions, SWMCS could produce more rainfall \( \mathcal{R}_{\text{tot}} = 3509.2 \text{ kg km}^{-2}\text{s}^{-1} \) than PFSL \( \mathcal{R}_{\text{tot}} = 3176.1 \text{ kg km}^{-2}\text{s}^{-1} \) with higher efficiency. The convective regions of SWMCS (53.1%) had higher PE than did PFSL (45.0%).

The diverse PEs of PFSL and SWMCS were associated with distinct synoptic, kinematic, and microphysical characteristics. The PFSL had deeper convection facilitated by pronounced vertical wind shear separating the up- and downdrafts. Subsequently, the PFSL associated with strong updrafts and frequent lightning activity featured more frequent graupel–rain mixing above the freezing level and graupel–small hail extending throughout the deep level. Instead, the SWMCS had shallower convection associated with uniform wind profile. The SWMCS had weaker updrafts and contained more snow and less graupel water content with reduced lightning frequency.

It is postulated that the higher wind shear of the PFSL reduces the PE by increasing the contact with drier environmental air and aiding evaporation of potential precipitation (Marwitz 1972). Moreover, the deeper convection with evaporative loss of rain that was transported upstream and that formed larger stratiform regions also reduced the PE of PFSL (Ferrier et al. 1996). In contrast, the SWMCS exhibited a higher downward increasing rate of liquid water content compared to PFSL. The deep warm cloud depth provided favorable conditions for accretional growth of rain. It is postulated that the SWMCS had higher PE as the higher liquid water content at low levels enhanced the accretional growth of rain.

During SWMCS, the long duration of rainfall due to the quasi-stationary MCSs is the main reason for the high accumulations of precipitation over the coastal area of southern Taiwan (Xu et al. 2012). Nevertheless, from the studies of synoptic, kinematic, and microphysical characteristics, the higher PE of SWMCS due to the aforementioned environmental factors and favorable microphysical processes also played critical roles in producing heavy rainfall. Despite the convective precipitation of the SWMCS having lower mean total water vapor flux \( \overline{Q}_{\text{tot}} \) than PFSL, it was still able to produce higher mean total rainfall flux \( \mathcal{R}_{\text{tot}} \) with higher efficiency.

This study provides the preliminary investigation of the subtropical PEs (i.e., those over southern Taiwan) during SoWMEX/TiMREX from observational data. Extending the PE study to various precipitation systems (e.g., mei-yu events, typhoons) is necessary as future work. Moreover, further detailed study of PE using numerical simulation with sophisticated microphysical parameterization schemes is required. By comparing the PE from numerical weather simulations and observational studies of various precipitation systems, quantitative precipitation forecasts (QPFs) can be improved by better describing the evolution of the precipitation processes.

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REFERENCES


