Radar Observations of the Diurnally Forced Offshore Convective Lines along the Southeastern Coast of Taiwan

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(Manuscript received 29 June 2004, in final form 4 November 2004)

ABSTRACT

This study documents offshore convective lines along the southeastern coast of Taiwan, a frequent but poorly understood mesoscale phenomenon that influences coastal weather during the Taiwan mei-yu season. Doppler radar and surface observations were gathered from a specially chosen period (11–15 May 1998) when the offshore convective lines were active off the southeastern coast of Taiwan. These observations were used to show the basic character, structure, and possible formative processes of offshore convective lines. The synoptic environment accompanying these events was found to be relatively undisturbed and featured uniformly prevailing southerly/south-southeasterly winds in the boundary layer with southwesterlies/westerlies aloft. Examination of radar data during the study period indicates that the lines generally occurred ~10–30 km offshore and were characterized by an elongated narrow zone (~5–10 km wide) of heavy precipitation. The lines were oriented roughly parallel to the coastline and generally did not move significantly. The intensity of the radar reflectivity associated with the lines exhibited a marked diurnal variation and was closely related to the coastal offshore flow developing at night.

Detailed analyses of an event on 14–15 May 1998 further show the important physical link between the offshore flow and the development of the line. The offshore line was found to be located near and immediately ahead of the seaward extent of the offshore flow. Particularly, a very narrow zone (~2 km) of low-level heavy precipitation (40–45 dBZ) coincided with regions of strong updrafts and convergence, where the prevailing southerly onshore flow encountered the cool offshore flow nearshore. This offshore flow–induced convergence, given a stable thermodynamic condition in the lowest ~1 km in the inflow region, was a crucial low-level forcing that provided lifting to trigger moist deep convection in this case. The line’s precipitation tilt eastward was confined primarily to the warmer inflow side rather than feeding the offshore flow to the west of the line. No consistent upshear tilt of updrafts throughout the storm layer was observed, which is consistent with the presence of a strong westerly shear in the line’s environment. Both of these observations explain a relatively strong (weak) modification of low-level onshore (offshore) flow by precipitation. Additionally, a combination of surface and Doppler radar observations indicates that the leading edge of the offshore flow moved seaward very slowly at 0.7 m s⁻¹ and possessed a frontal character with notable discontinuities in near-surface wind and temperature (instead of pressure and dewpoint temperature).

1. Introduction

During the late spring and early summer months, a period known in Taiwan as the mei-yu season (Chen 1983), two well-known mesoscale phenomena occur frequently off the southeastern coast of Taiwan: mesolows and offshore convective lines, both of which significantly influence coastal weather and the distribution of precipitation over this local area (Chen 1992; Chu and Liu 2001). In contrast to the understanding of the mesolows, which has been largely explored by previous studies, various observational aspects of the offshore convective lines still lack good documentation, particularly the physical processes that contribute to their formation. In this paper, we present results from analy-
ses of radar and surface measurements gathered from a specially chosen period when the convective lines were active off the southeastern coast of Taiwan during 11–15 May 1998. We will show the low-level convergence induced by the land-breeze circulation to be crucial to the formation of the observed convective lines, and some key aspects concerning their precipitation characteristics and airflow structures will also be discussed.

It is well recognized that island or peninsula convection can be strongly modulated by the land/sea breezes developing in coastal regions. This topic has been addressed by numerous studies over different geographical regions (e.g., Takahashi 1977; Garrett 1980; Keenan and Carbone 1992; Kingsmill 1995; Wilson and Megenhardt 1997; Carbone et al. 2000). These previous investigations indicate that boundary layer convergence, resulting from the collision of the land-sea-breeze fronts and synoptically prevailing flow, is a common forcing for the initiation of moist convection in the vicinity of islands. Nevertheless, subsequent development and organization of island moist convection is usually more complicated and less understood due to complex interactions between land/sea breezes, precipitation effects (such as the presence of convectively generated cold pools), and environmental kinematics and thermodynamics (e.g., Kingsmill 1995; Carbone et al. 2000). For islands with significant topography, in addition to the forcings associated with land/sea breezes, thermally induced katabatic/anabatic flow and circulations produced by orographic blocking may also play a vital role in influencing the formation and development of clouds and precipitation over islands (e.g., Feng and Chen 1998; Frye and Chen 2001).

Taiwan is a mountainous island, and the land/sea breeze characterized by the offshore (onshore) flow during the nighttime (daytime) hours frequently dominates wind patterns within the boundary layer during the mei-yu season (Chen 1992). These diurnal circulations have been found to strongly affect the modulations of heavy rainfall around Taiwan, particularly when the synoptic environment is characterized by relatively undisturbed conditions and the influence of mei-yu fronts is relatively small (Chen and Yang 1988; Chi and Chen 1989; Chen et al. 2001). Observations collected as part of the Taiwan Area Mesoscale Experiment (TAMEX; Kuo and Chen 1990) have revealed some limited aspects of diurnal circulations and their possible relationship with precipitation. For instance, Lin and Sheng (1990) used pibal data to investigate the basic features of land/sea breezes over the southwest plain of Taiwan. They found that sea breezes generally occur in the lowest 1 km MSL and have a return flow at ~1.5 km MSL.

Meanwhile, land breezes were observed to be weaker and confined to the lowest 0.5 km MSL. By analyzing surface measurements during synoptically undisturbed periods, Johnson and Bresch (1991) found a tendency for convective precipitation to occur during the late morning and early afternoon at 100–500 m MSL along the east/west slopes of Taiwan. They suggested that this convective precipitation resulted from the inflowing sea-breeze air encountering an abrupt rise in the topography. Several recent studies have used high-resolution observations from Doppler radars to examine additional aspects of diurnally forced precipitation systems (e.g., Jou 1994; Chen et al. 1999). As indicated by these studies, the enhanced convergence produced by the interaction between the sea-breeze circulation and the storm-generated cold outflow is an important low-level forcing for maintenance of convection within the observed precipitation systems.

Because all of these previous studies focused on precipitation systems in western Taiwan (i.e., including both northwestern and southwestern Taiwan), our understanding of the nature of diurnal circulations and their impact on the development of moist convection

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**Fig. 1.** Topography in southern Taiwan. Terrain height (m MSL) is indicated by shading at 500-m intervals (key at top). Location of the Doppler radar site at Green Island (GI) is denoted by the triangle. Locations of select surface observing stations [Chengkung (CK), Taitung (TT), Tawu (TW), Hengchun (HC), and Lanyu (LY)] and sounding stations [Tungkang (TK) and GI] are denoted by hollow circles and squares, respectively. The large heavy circle refers to the 120-km observational range of the GI radar.
along the eastern coast of Taiwan have been relatively unexplored. In contrast to the western coast of Taiwan, the topography of eastern Taiwan is characterized by an exceptionally steep south-southwest–north-northeast oriented barrier, along which the terrain rises abruptly to more than 1500 m MSL within 20 km of the shore (cf. Fig. 1). The basic characteristics of diurnal circulations along the extreme slope of the coastal mountains differ inherently from those along the western coastal plain. Few earlier studies have provided evidence that the east-facing steep mountain slopes contribute to stronger downslope flow and an earlier onset of land-sea-breeze circulations along the eastern coast during the mei-yu season (Johnson and Bresch 1991; Sun and Chern 1993). Recent studies by analyzing measurements collected during the Green Island Mesoscale Experiment (GIMEX; Jou and Shieh 2001), which was conducted over southeastern Taiwan in May–June 2001, further indicated that the diurnal circulations along the southeastern coast of Taiwan exhibited an obvious along-coast variation in terms of their depth and onset (Leu and Lin 2004; Chien and Lin 2004). This characteristic was evidently attributed to the influences of thermally induced katabatic/anabatic flow over the Coast Range (Fig. 1) and the up-valley (downvalley) winds (Banta et al. 1990) flowing out of the valley between the Central Mountain Range and the Coastal Range. The deployment of a C-band (5 cm) ground-based Doppler radar on Green Island in late 1997 (see Fig. 1 for radar location) provided a valuable opportunity to document diurnally forced moist convection along the eastern coast of Taiwan. Using measurements from the Green Island radar, this study investigates the basic characteristics and structure of the convective lines occurring off the southeastern coast during the mei-yu season and shows how the diurnal circulations relate to offshore convective activity.

It is noteworthy that some observational aspects regarding offshore moist convection induced by diurnal forcings have been described for other tropical coasts (e.g., Kousky 1980; Houze et al. 1981; Smolarkiewicz et al. 1988; Mapes et al. 2003). Among these, a typical and well-documented example are so-called Hawaiian cloud/rainbands frequently present offshore in the early morning on the windward side of the island (Smolarkiewicz et al. 1988). Initiation of these offshore rainbands is believed to be closely related to the convergence zone between the offshore flow (resulting from a combined effect of the katabatic flow and coastal land-breeze circulation) and the incoming trade winds (Takahashi 1977; Garrett 1980; Wang and Chen 1998; Li and Chen 1999). Nevertheless, current understanding of physical processes responsible for the subsequent development of these offshore bands is limited and inadequate. Particularly, similarities and differences between the Hawaiian rainbands and the squall lines, in terms of their structure and dynamics, remain ambiguous (Takahashi 1988; Takahashi et al. 1989; Raga et al. 1990; Wang and Chen 1998). For instance, both storm systems had a sloped updraft with enhanced low-level convergence at their leading edge. Conversely, the convectively evaporative cold dome and strong nonhydrostatic effect, both of which have been thought to be essential to the maintenance of deep moist convection within the squall lines (Rotunno et al. 1988; Weisman et al. 1988), do not appear to be characteristic of the Hawaiian rainbands (Takahashi 1988; Takahashi et al. 1989). Regardless of the differences in geographical location and synoptic environment, the present study examines the general understanding of diurnally forced moist convection occurring off a mountainous island coast.

The rest of this paper is organized as follows. Section 2 introduces the data used in this study. Section 3 summarizes the basic characteristics of observed radar echoes associated with the convective lines during 11–15 May 1998, with an emphasis on their relationship with

<table>
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<td>Max unambiguous velocity</td>
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diurnal forcing. Section 4 presents results from the detailed analysis of a strong event on 14–15 May 1998 and also discusses some important structural aspects of the line. Major findings are summarized in section 5.

2. Data

The primary datasets used in this study were provided by the Weather Wing of the Chinese Air Force operational C-band (5.33 cm) Doppler radar on Green Island and include volumetric distributions of reflectivity and radial velocity. Table 1 summarizes the characteristics of the Green Island radar. Since the radar is situated ~40 km offshore and adjacent to the steep coastal barrier in southern Taiwan (Fig. 1), raw measurements from lower scanning elevations frequently contain contamination due to ground/mountain clutter. The contaminated echoes and obviously spurious data were corrected interactively. During the 5-day analysis period (11–15 May 1998) about 480 scanning volumes of radar data were collected, with a temporal interval of ~15 min between each volume. Figure 1 also indicates other data sources used in this study, including routine surface and island observations within the coastal zone of southeastern Taiwan and two available soundings (Green Island and Tungkang) within the study region.

3. General features of the lines and their relation to diurnal forcing

Figure 2 summarizes the basic radar echo features of the offshore convective lines observed by the Green
Island (GI) radar during 11–15 May 1998. Each panel in Fig. 2 represents the time when the lines were in their most organized stage. The convective lines were generally located 10–30 km offshore and oriented roughly south-southwest–north-northeast, and hence were roughly parallel to the southeastern coast of Taiwan. The lines were marked by multiple centers of heavy precipitation concentrated within an elongated, narrow 5–10-km-wide zone. Maximum radar reflectivities along these lines generally exceeded 40 dBZ. Particularly on 13 and 15 May (Figs. 2c,d), the reflectivity values exceeded 45 dBZ. Notably, the lines generally were

**Fig. 3.** Time series of hourly surface observed winds during 11–16 May 1998 from CK, TT, and TW stations. The offshore flow component defined as the wind component perpendicular to the mean orientation of the coastline (~25° clockwise from the north) is indicated by the solid line with the positive value representing the wind toward the ocean. In each panel, shaded areas refer to the period dominated by the offshore flow. Full wind barbs correspond to 5 m s$^{-1}$; half barbs to 2.5 m s$^{-1}$. The heavy arrow on the right side of each panel indicates the wind transition associated with the passage of the mei-yu front.
Fig. 4. The Central Weather Bureau (CWB) mei-yu front isochrones with 12-h intervals from 0800 LST 11 May to 0800 LST 16 May 1998.

Fig. 5. Temporal variation of offshore convection along the southeastern coast of Taiwan during 11–15 May 1998. The low-level PPI scan (1° elevation) of radar reflectivity from the GI radar was projected onto a section parallel to the coast and plotted as a function of time. The offshore flow component (as denoted by solid lines) observed at CK, TT, and TW is superimposed on the reflectivity field. The vertical heavy dashed line indicates the arrival of the leading edge of precipitation associated with the mei-yu front. Daytime transient precipitation is denoted by dashed circles.
quasi stationary, as indicated by a sequence of the plan-
position indicator (PPI) scans of radar reflectivity dur-
ing the life cycle of these lines (not shown).

During 11–15 May, the synoptic environment in the
vicinity of southeastern Taiwan was relatively undis-
turbed and featured south-southeasterly winds at near-
surface levels (further described in section 4). Time se-
ries of hourly surface observations from three stations
along the southeastern coast (Chengkung, Taitung, and
Tawu; Fig. 1) reveal the important evolution of surface
winds immediately west of the offshore convective
lines, as presented in Fig. 3. During this period, the
coastal surface winds were relatively weak and less than
4–5 m s\(^{-1}\). Furthermore, they exhibited a clear diurnal
variation, with offshore flow prevailing at night and
onshore flow during the day. This trend indicates the
development of land-sea-breeze circulations along the
coastal zone. The time of onset of the offshore flow
varied from day to day, but was generally around 1830
LST (LST = UTC + 8 h). The offshore flow ceased at
approximately 0800 LST. The onset (and end) of the
offshore flow at Chengkung (Fig. 3a) appeared to be
about 1–2 h earlier than that observed at the Taitung
and Tawu stations (Figs. 3b,c). As shown in Fig. 1, the
Chengkung station is located immediately adjacent to
the highest terrain (\(~1.5\) km MSL) and the steepest
slope of the Coastal Range. The earlier onset of the
offshore/onshore flow at Chengkung compared to else-
where suggests a direct influence of thermally driven
slope breezes on the development of the coastal land/
sea breezes caused by the land–sea thermal contrast
(Mahrer and Pielke 1977). Similar findings have also
been reported in GIMEX observational and numerical
modeling studies of diurnal circulations over southeast-
ern Taiwan (Leu and Lin 2004; Chien and Lin 2004).

It should be noted that the diurnal variation of
coastal surface winds were not disturbed evidently by
the synoptic flow associated with the mei-yu front\(^2\) until
\(~1200\) LST 15 May (Fig. 3). As shown in Fig. 4, prior to
2000 LST 14 May the mei-yu front was located \(~100–300\) km north of Taiwan and remained quasi stationary.
After 2000 LST 14 May, the front, however, progressed
persistently southeastward and made landfall on Tai-
wan at 0800 LST 15 May. Consistent with the passage of
the front in southern Taiwan around 2000 LST 15 May
(Fig. 4), coastal surface observations seen in Figs. 3a,b
experienced an obvious wind transition from prefrontal
southwesterlies to postfrontal northerlies/northwester-
lies during this period.

\(^2\) Details about the definition and characteristics of a mei-yu
front can be found in Chen (1992).
ity along the direction normal to the coast was selected to represent precipitation intensity at that coastal location. To illustrate the possible influence of offshore (onshore) flow on the development of the offshore convective lines, the offshore (onshore) flow component observed at Chengkung, Taitung, and Tawu (shown in Fig. 3) are also superimposed in Fig. 5. The intensity of precipitation associated with the offshore convective lines clearly exhibited a pronounced diurnal variation. The lines tended to develop at night and rapidly weakened and dissipated after sunrise. The time when the precipitation of the offshore line reached its most intense stage varied each day, but generally coincided with the period of coastal offshore flow. Figure 5 also reveals some precipitation other than the offshore convective lines. For example, relatively short-lived and localized precipitation (highlighted by dashed circles in Fig. 5) was also evident during daytime hours. However, these precipitation patterns seen were in fact a result of the presence of a few convective cells forming randomly ~60–120 km offshore, as illustrated by two selected PPI scans of radar reflectivities at 1200 LST 13 May and 1400 LST 14 May (Fig. 6). In contrast to the nighttime offshore convective line, these daytime precipitation elements were disorganized and very transient. Because the frequency of occurrence of these scattered oceanic precipitation echoes and their intensity tended to reach maximum near noon each day.

Fig. 7. Time sequence of 1° elevation of PPI scan of radar reflectivity (dBZ) from the Green Island radar showing the evolution of offshore convection along the southeastern coast of Taiwan at (a) 1930, (b) 2130, (c) 2330, (d) 0130, (e) 0330, (f) 0530, (g) 0730, and (h) 0930 LST 14–15 May 1998. In each panel, solid arrows denote the precipitation elements associated with the studied convective line.
(Fig. 5), daytime solar heating is likely to be an important factor for their development. Note also that following 1200 LST 15 May the leading edge of widespread precipitation associated with the approaching mei-yu front had just reached the southeastern coast of Taiwan, as clearly seen in a sequence of PPI scans of Green Island radar (not shown). The studied region was largely influenced by frontal precipitation since that period (Fig. 5).


a. Case overview

As shown in Figs. 2 and 5, good radar coverage of the offshore convective line on 14–15 May 1998 provides valuable airflow information within the line that allows investigation of the physical link between the line and the diurnal circulations. The evolution of low-level reflectivity is summarized in Fig. 7. The precipitation echoes associated with the line were initiated 10–15 km offshore at about 1930 LST on 14 May (Fig. 7a). During this early stage, the offshore convection was relatively weak with radar reflectivity generally below 35 dBZ and confined to a coastal area immediately upstream of the Coastal Range (e.g., near the Chengkung surface station). In contrast to the lack of obvious offshore flow prevailing along the coast south of the Coastal Range during this time (Figs. 3b,c), the surface winds observed at Chengkung had a westerly component and thus had already turned offshore (Fig. 3a). Therefore, an earlier onset of offshore flow in this particular region is consistent with the offshore convection first occurring off
the Coastal Range. Subsequently, the precipitation intensified, and new convective elements developed to extend the zone of active convection southward (Fig. 7d). By 0330 UTC, the convective line reached its maximum intensity and became highly organized and characterized by an elongated but narrow zone of heavy precipitation approximately parallel to the coast (Fig. 7e). As the coastal offshore flow weakened following sunrise (Fig. 3), the offshore line broke into discrete precipitation elements and dissipated rapidly (Figs. 7g,h).

The surface analysis at 2000 LST 14 May (close to the time of initiation of the offshore convection on that day) shows a northeast-southwest-oriented mei-yu front and its associated pressure trough located ~250 km north of Taiwan (Fig. 8). An elongated cloud shield marked the synoptic mei-yu front, extending northeastward from southeastern China to a location south of

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**Fig. 8.** Sea level pressure analysis valid at 2000 LST (i.e., 1200 UTC) 14 May 1998. Full wind barbs correspond to 5 m s⁻¹, half barbs to 2.5 m s⁻¹. The heavy thick line denotes the position of the mei-yu front.
Japan (Fig. 9). As described in section 3, the mei-yu front started to advance southeastward at an average speed of \( \sim 5-6 \text{ m s}^{-1} \) during this period. Over southeastern Taiwan, surface winds generally came from the south and were mainly controlled by the large-scale circulations associated with the subtropical high over the western Pacific. Prevailing winds brought a weak onshore flow of \( \sim 2-3 \text{ m s}^{-1} \) on the eastern coast of Taiwan. The vertical thermodynamic and wind profile from a sounding taken at Green Island indicates that low-level winds veered with height from southerly/south-southeasterly near the surface to westerly at around 850 mb and above (Fig. 10). Stable-to-neutral convective stability was found below 1.5 km (MSL), with considerable convective instability aloft. A relatively dry layer marked by an enhanced inversion was present near 1 km (MSL). The sounding taken from the Tungkang station upwind of the mountain (see Fig. 1 for the location) also displays evidence of this type of temperature inversion at a similar height. Hence, it is unlikely that this observed shallow stable layer was caused by leeside subsidence of the upper-level prevail-
ing westerlies as they flow over the topography of southern Taiwan; instead, the presence of this layer should be related to large-scale subsidence in association with the synoptic subtropical high located east of Taiwan (Fig. 8).

In the presence of relatively weak synoptic forcings during the period of interest, mesoscale airflow patterns over southeastern Taiwan were basically characterized by a quasi-steady condition. Some important mesoscale features in the vicinity of the offshore line can be representatively revealed by surface observations of winds and thermodynamics at ~0300 LST 15 May when the line was at its highest organized stage (Fig. 11). To the west of the line, winds (1–2 m s⁻¹) along the southeastern coast were generally directed offshore, indicating that the land-breeze circulation dominated at near-surface levels. In contrast to the offshore flow found near the coast, slightly stronger southerly winds (thus directed onshore) were observed to the east of the line. The presence of the southerly flow offshore is consistent with the large-scale airflow patterns in the vicinity of southeastern Taiwan as presented in Fig. 8. It is noted that wind patterns as shown in Fig. 11 did not alter much with time. This aspect can be readily seen from a time sequence of surface observations from two selected stations at Lanyu (located ~60 km offshore) and Taitung (located on the coast) on 14–15 May 1998, as shown in Fig. 12. Surface winds observed offshore at Lanyu were southerly and remained nearly constant with time in both direction and magnitude, indicating a characteristic typical of undisturbed weather conditions. Despite the wind transition of the land/sea breeze (offshore/onshore flow marked by arrows in Fig. 12), surface winds observed at Taitung

Fig. 10. Skew T–logp plot of the GI sounding taken at 2000 LST 14 May 1998. Full wind barbs correspond to 5 m s⁻¹, half barbs to 2.5 m s⁻¹.
were basically westerly and/or northwesterly and directed toward offshore with a slight variation in wind speed from midnight to early morning.

Figure 11 also shows that the potential temperature observed along the southeastern coast of Taiwan was about 1.5 K colder than that observed ~35 km offshore. This baroclinic zone was accompanied by a pronounced wind transition between the relatively cool offshore flow near the coast and the warmer prevailing southerlies offshore, a signature of the land-breeze front oriented parallel to the coast. The baroclinicity within the coastal zone, as measured by the difference in temperature between Taitung and Lanyu, peaked with a temperature difference of 2.5 K between the two stations in the early morning around 0600 LST (Fig. 12). Note that the temperature difference across the coast was enhanced primarily through the persistent radiation cooling over land after sunset, while the temperature of the relatively warm, ocean-modified air farther offshore remained almost constant with time overnight, a typical characteristic of the nocturnal marine boundary layer (Stull 1988). Owing to a relatively coarse spatial resolution in surface observations within the coastal zone, the analysis presented in Fig. 11 cannot document the finescale structures of the observed land-breeze front. Nevertheless, some more detailed aspects for the front can still be obtained with the use of high temporal resolution of surface observations as the front passed the coast during the earlier period. Figure 13 illustrates the temporal variation of surface temperature, dewpoint temperature, wind, and pressure at 2-min intervals, which was recorded at Taitung between 1900 LST 14 May and 0200 LST 15 May. At 2234 LST 14 May, the temperature rapidly decreased and the wind direction and speed changed sharply, indicating the passage of the leading edge of the land-breeze front. These changes (1°C, 1.5 m s⁻¹, and 55° for temperature, wind

FIG. 11. Analysis of surface potential temperature (dashed lines) with contour interval of 0.5 K at 0300 LST 15 May 1998. Gray shading over land indicates terrain height while gray shading over ocean indicates radar echoes associated with the studied convective line at the analysis time. Radar reflectivities associated with the convective line along a coastal segment marked by two thin lines are shown in Fig. 15. Observed surface wind vectors (key at upper right) are also indicated.

FIG. 12. Hourly time series of potential temperature observed at TT (solid line) and LY (dashed line) from 1200 LST 14 May to 1200 LST 15 May. Winds observed from these two stations are also indicated; full (half) wind barbs correspond to 5 (2.5) m s⁻¹. Arrows denote the transition of onshore/offshore flow observed at TT.
speed, and wind direction, respectively) were concentrated within a period of 30 min. The temperature continued to decrease gradually after the front had passed. Discontinuities in dewpoint temperature associated with the front were minor, but the dewpoint temperature began to fall markedly at 0000 LST 15 May, indicating the arrival of more cool and dry air after the passage of the front. The dewpoint temperature dropped 3°C by 0200 LST 15 May. These temporal variations qualitatively resemble those of a midlatitude land-breeze front reported by Meyer (1971) who also showed much more pronounced changes in temperature and winds compared to dewpoint changes during the passage of his observed fronts. The peak values of surface pressure shown in Fig. 13 were found to be between 2200 and 2300 LST 14 May, a period close to the frontal passage, but no obvious pressure jump occurred near the front.

Along the southeastern coast of Taiwan, the precise location of the land-breeze front and the leading edge of the coastal offshore flow may be obtained by noting the discontinuities in the direction/magnitude of the radial velocities from low-elevation Green Island Doppler radar observations. A frontal isochrone analysis using the 0.1° elevation scan (Fig. 14), undertaken by tracking the zero radial velocity line, illustrates the seaward propagation of the near-surface frontal wind shift along the coastal segment near Taitung. Consistent with the surface observations from Taitung showing the passage of the land-breeze front around 2234 LST (Fig. 13), the Doppler-observed frontal wind shift was coincident with the coastline at 2225 LST (Fig. 14a). The land-breeze front moved seaward very slowly at a mean moving speed of only 0.7 m s$^{-1}$ between 2225 and 0325 LST, although some variation in frontal movement was also evident. It is noted that the intensity of precipitation associated with the land-breeze front remained

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$^3$ Radar data used herein to track the movement of the land-breeze front were collected during a time when the radar system was operated with higher transmitter power and reduced noise power (the so-called clear-air scanning mode). This observing strategy was performed hourly and the radar scanning was confined only to low elevations (below 2° elevation). Because of higher detection sensitivities, these scans were able to provide additional wind information along the coastal zone during the early period before the development of significant precipitation found along the land-breeze front (detailed later in text).
quite weak during this earlier period. A select PPI scan of radar reflectivity and radial velocity at 0025 LST (Fig. 14b) indicates that a narrow zone of light precipitation (<10 dBZ) oriented approximately parallel to the land-breeze front were located near and immediately ahead of the frontal wind shift. As will be demonstrated in section 4b, intense precipitation echoes did not develop along the frontal wind shift until 0245 LST 15 May.

b. Radar-derived structure of the line

As shown in Fig. 7, the observed radar reflectivity was best organized and exhibited highly two-dimensional features at about 0330 LST (Fig. 7e). During this interval, it is reasonable to consider the convective motions within the line in a two-dimensional sense, ignore variation in the along-line direction, and obtain detailed normal-line circulations retrieved from the

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**Fig. 14.** (a) Isochrones of the zero radial velocity (0 m s\(^{-1}\)) line from the 0.1° elevation PPI scan from the GI Doppler radar depicting the horizontal wind shift associated with the passage of the land-breeze front from 2225 LST 14 May to 0325 LST 15 May. (b) Radar reflectivity (dBZ, shading) and corresponding radial velocity (contour interval 0.5 m s\(^{-1}\)) from the 0.1° elevation PPI scan at 0025 LST 15 May. Positive and negative values of radial velocity denote the flow toward and away from the radar, respectively. The thick heavy line marks the zero radial velocity line associated with the land-breeze frontal wind shift. Location of TT is also indicated.
ranged–height indicator (RHI) vertical cross section perpendicular to the line (Wakimoto 1982). The normal-line horizontal velocities were approximated by the horizontal component of adjusted Doppler velocities that had the contribution of particle terminal velocity removed. The empirical relationship between fall speed and radar reflectivity as described in Jorgensen et al. (1991) was used to estimate the terminal velocity of precipitation particles for a subtropical convective system. Within the line, the largest elevation angle of radar beams is no greater than 10° below 5 km (MSL) and thus the small component of the Doppler velocity contributed by the vertical air motions was initially neglected. Once the normal-line horizontal velocity (and convergence) was obtained, the vertical velocity was then computed by integrating the anelastic continuity equation. Because the component of vertical motions contributed to the observed value of radial velocities more significantly at larger elevation angles, the accuracy of calculated horizontal motions and convergence was reduced at higher storm levels. To mitigate errors in derived vertical velocities resulting from this inherent limitation, the upward integration was applied from a lower-boundary condition of zero vertical motion at the ground. Such a procedure provides better (less) reliability of derived vertical velocities at lower (upper) levels within the storm.

Detailed views of low-level precipitation associated with the offshore line along a coastal segment near Taitung (as indicated by two thin lines in Fig. 11) around 0330 LST are illustrated in Fig. 14. Obvious precipitation along this segment started at 0245 LST and remained approximately two-dimensional until 0415 LST, when it broke into several discrete elements. Results from two representative RHI cross sections (AA’ and BB’ in Fig. 15) are presented herein to illustrate the primary precipitation and airflow structures of the line during this period. The radar-derived normal-line precipitation and wind along AA’ is displayed in Fig. 16b, and for comparison, raw radial Doppler velocity along this cross section is also shown in Fig. 16a. Because the line’s orientation is nearly parallel to the coast (Fig. 7e), low-level normal-line winds can be considered as offshore/onshore flow. The vertical section shown in Fig. 16a reveals that the precipitation of the offshore line exhibited a significant vertical extent (the 35-dBZ con-

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**Fig. 15.** The 1° elevation PPI scan of radar reflectivity (dBZ) from the GI radar showing low-level precipitation features of the offshore convection during 0245–0415 LST along a coastal segment (as indicated by two thin lines in Fig. 11) near TT on 15 May 1998. The heavy thick arrows mark the location of the vertical cross section A and B shown in Figs. 16 and 18.

**Fig. 16.** (a) RHI display of radar reflectivity (dBZ, shading) and corresponding radial velocity (contour interval 1 m s⁻¹) at 0315 LST from the Green Island radar along A (location of the vertical section marked in Fig. 15) approximately perpendicular to the line and coast. Positive and negative values of radial velocity denote the flow toward and away from the radar, respectively. (b) Same as in (a) except showing derived cross-line winds (indicated by wind vectors; key at upper left), and the corresponding radar reflectivity (dBZ) is also indicated by the contours. The letter U (D) in (b) denotes the regions of primary upward (downward) vertical motions.
FIG. 16. (Continued)
tour exceeding 4 km MSL) and strong horizontal gradients, indicating the convective nature of the precipitation. The observed echo top exceeded 7–8 km MSL, which was much lower than the equilibrium level (∼13.5 km MSL) as illustrated in the environmental sounding (Fig. 10). This suggests that the entrainment process may play a significant role in reducing in-cloud buoyancy for subtropical oceanic convection (Jorgensen and LeMone 1989). However, when considering air parcels of a mixed-layer origin, they would follow a colder pseudoadiabat and have correspondingly lower convective available potential energy and equilibrium level. The radial Doppler velocity patterns within the line with negative values (away from the radar) in the lowest 1 km and positive values (toward the radar) at upper levels generally reflect the characteristics of environmental airflow observed to the east of the line (Fig. 17). Note that the region of negative velocity extends rearward (westward) and upward to higher altitudes (1–3 km MSL). This is consistent with the upward transport of horizontal momentum associated with the low-level southerly inflow by convective updrafts within the line.

As described in section 4a, the offshore convective line was located in the region between the near-surface prevailing southerlies offshore and the generally westerly and/or northwesterly offshore flow near the coast (Fig. 11). The analysis presented in Fig. 16b further shows that the low-level southerly inflow entered the system from the east, and began to be lifted immediately ahead of the leading edge of the offshore flow. Particularly, a very narrow zone (2 km) of low-level heaviest precipitation (≥40–45 dBZ) coincided with strong updrafts (maximum derived vertical velocity of ∼4 m s⁻¹) and convergence between the southerly onshore flow and the cool offshore flow. Intensity of the offshore flow was about 1–2 m s⁻¹ and analogous to that observed on the coast (Fig. 11). Also, its vertical depth was shallow and appeared to be confined to the lowest 1 km MSL. Furthermore, the contour pattern of radial Doppler velocity associated with the offshore flow became more elevated toward its leading edge (Fig. 16a), a feature highly similar to the raised density-current-like head of sea/land breezes previously documented by Simpson and Britter (1980) and Ohara et al. (1989).

At mid- to high levels, environmental dry air associated with the prevailing westerlies (Figs. 10 and 17) intruded into the precipitation region from the west, where the descending motions (D3 in Fig. 16b) were also evident. The presence of this intruding air is consistent with the rapid dissipation of upper-level cloud/precipitation observed at a later time (Fig. 18). Such a characteristic of the line is actually in contrast to that of some previously documented Hawaiian rainbands, whose ambient air did not intrude into the cloud system and thus its associated convection could last much longer (Takahashi 1988; Takahashi et al. 1989). Some other weaker downdrafts (D1 and D2 in Fig. 16b) are found at lower levels (∼2 km MSL) on both sides of the main updraft region. These downward motions were located in regions of relatively low reflectivity and as such, were probably not driven directly by water loading. Their occurrence is more likely to be caused by compensating subsidence accompanying the primary updraft and/or by negative buoyancy associated with evaporation of precipitation (Knupp and Cotton 1985).

The radar-derived normal-line precipitation and winds along the other RHI cross section (BB') is shown in Fig. 18. Despite a lower storm height (4–5 km MSL), which corresponded to the generally weakening of precipitation during this time (Fig. 15), airflow structures of this cross section resemble those along AA'. As in Fig. 16, the low-level heaviest precipitation and updrafts were collocated with the zone of convergence.
Fig. 18. Same as in Fig. 16 except at 0345 LST and showing results along B (location marked in Fig. 15).
formed near the flow boundary between the offshore flow near the coast and the environmental onshore flow. It is noteworthy that, given the stable thermodynamic profile in the inflow region beneath 1 km (Fig. 10), the low-level convergence produced by the interaction between the nearshore cool offshore flow and the synoptically prevailing flow provides crucial low-level forcing that gives additional lifting to trigger moist convection. In Fig. 18, an onshore flow component of ~5 m s\(^{-1}\) that was stronger than the environmental normal-line wind east of the line (Fig. 17) and that along AA’ (Fig. 16a) was observed near the surface, but the offshore flow west of the line had a magnitude nearly same as that observed earlier (Fig. 16). Maximum magnitudes of onshore/offshore flow as observed from a sequence of radar measurements (listed in Table 2) indicate that the onshore flow component increased persistently with time and was obviously greater than its ambient value as the precipitation of the line intensified (Fig. 15). A slight decrease in the onshore flow component was found following the weakening of the line’s precipitation (i.e., after 0345 LST). In contrast, the intensity of the observed offshore flow remained essentially constant with time, with magnitudes comparable to its ambient value. The fact that a relatively strong (weak) modification of low-level onshore (offshore) flow by precipitation was evident can be understood as a consequence of the line’s precipitation being tilted eastward vertically and confined primarily to the region ahead of the seaward extent of the offshore flow (the warmer inflow side), rather than feeding the nearshore colder air mass present to the west of the line (Figs. 16 and 18). Given unsaturated environmental conditions at low levels east of the line (e.g., Fig. 10), intensification of onshore flow due to latent cooling produced by evaporating hydrometeors is expected to be significant (Table 2). In addition, as shown in Figs. 16 and 18, the updraft sloped slightly westward (i.e., upshear tilt) below ~2 km MSL while it tended to be tilted eastward aloft. The lack of a consistent upshear tilt of updrafts throughout the storm layer corresponded to the environmental wind profile (Fig. 17) that indicates a pronounced westerly vertical shear below ~2.5 km MSL and relatively weak shear with westerly momentum aloft. This structural characteristic is basically detrimental to the generation of a strong and large cold pool.

![Diagram](image_url)

**Fig. 19.** Two-dimensional schematic vertical cross section depicting an offshore flow–forced convective line observed off the southeastern coast of Taiwan on 14–15 May 1998. This section is oriented approximately northwest–southeast perpendicular to the coast and the line. The heavy solid arrows indicate salient airflow features in the vicinity of the line, and shading denotes main precipitation associated with the line. A heavy dashed line represents the boundary of the offshore flow and the “L” represents an approximate horizontal scale of the seaward extent of the offshore flow. The environmental wind profile in the cross-line direction is also indicated in the right-hand portion of the figure.

**Table 2.** Doppler radar–observed maximum magnitudes of low-level onshore/offshore flow component during the evolution of the convective line. Ambient values of onshore/offshore flow to the east/west of the line, as seen from surface and sounding observations, are also indicated for comparison. Information on offshore flow is missing at some analysis periods due to the lack of radar return echo.

<table>
<thead>
<tr>
<th>Time (LST)</th>
<th>0230</th>
<th>0245</th>
<th>0300</th>
<th>0315</th>
<th>0330</th>
<th>0345</th>
<th>0400</th>
<th>0415</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Onshore flow (m s(^{-1}))</td>
<td>~2</td>
<td>2–3</td>
<td>~3</td>
<td>3–4</td>
<td>4–5</td>
<td>5–6</td>
<td>4–5</td>
<td>~4</td>
</tr>
<tr>
<td>Offshore flow (m s(^{-1}))</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
<td>—</td>
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</tr>
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and to the organization of the convection into a fast-moving, long-lived convective system (Rotunno et al. 1988).

c. Movement of the land-breeze front

A significant number of observational studies have discussed similarities between the leading edge of an atmospheric (land) sea-breeze front and laboratory (density) gravity currents in terms of kinematic structure and moving speed (Simpson 1969; Schoenberger 1984; Ohara et al. 1989; Wakimoto and Atkins 1994; Carbone et al. 2000). According to the results of a laboratory experiment conducted by Simpson and Britter (1980), the speed of a density current can be approximated by the following expression:

$$ C = k \left[ \frac{gh(\theta_2 - \theta_1)}{\theta_2} \right]^{1/2} + 0.6u_0, \quad (1) $$

where $g$ denotes the gravitational acceleration, $h$ represents the depth of the cold air; $\theta_1$ and $\theta_2$ are the cool and warm airmass virtual potential temperature, respectively; $u_0$ denotes the head wind speed in the direction perpendicular to the front (negative for a wind toward the cool air mass); and $k$ represents the internal Froude number. Theoretically, the value of the internal Froude number expressed in (1) is variable (between 0.7 and 1.4; Benjamin 1968) and has been shown to be a function of the ratio between the depth of the cool air mass and total fluid depth (Simpson and Britter 1979; Smith and Reeder 1988). When the density-current dynamic is assumed to be the sole mechanism governing movement, the internal Froude number ranges from 0.5 to 1.1 for atmospheric sea-breeze fronts (Wakimoto and Atkins 1994; Carbone et al. 2000).

As described in section 4a, the combination of surface and Doppler radar observations show that the present land-breeze front moved seaward at a mean moving speed of $C = 0.7 \text{ m s}^{-1}$. The mean $u_0 = -3.3 \text{ m s}^{-1}$ is estimated by winds observed at Lanyu, while $\theta_1 = 302.8 \text{ K}$ and $\theta_2 = 303.6 \text{ K}$ are average values observed at Taitung and Lanyu, respectively, during the interval. The Doppler-derived flow fields indicate the depth of the cold air to be maximum at $\sim 1000 \text{ m}$ (Figs. 16b and 18b). However, this observed value is expected to be more representative of the height for the leading edge of the cold air, rather than the depth of the cold air feeding its leading edge [i.e., the height scale applied in (1); Simpson and Britter 1980]. As indicated by previous observational and experimental studies (Meyer 1971; Ohara et al. 1989), the height of the land-breeze head (the leading edge) is usually several times larger than the depth of the land-breeze layer behind it due to convective motions associated with the collision between the cold air at the back and the warm air at the front. To obtain a height scale more suitable for approximating $h$ in (1), the observed value of the cold air depth was subtracted from an excess height ($h'$) of the density-current head above the following cold air. According to Simpson and Britter (1979), $h'$ can be approximated by the following expression:

$$ h' = 0.52 \times \frac{\theta_2 \Delta V^2}{g(\theta_2 - \theta_1)^1}, \quad (2) $$

where $\Delta V$ denotes the difference in velocity between the cold and warm air mass. It is clear from (2) that larger differences in velocity between the cold and warm air mass will cause an increase in the excess height. In this case, $\Delta V$ is found to be $\sim 5 \text{ m s}^{-1}$ (cf. Fig. 16), giving a height scale of $h' = 500 \text{ m}$ and a resulting cold air depth of $h = 500 \text{ m}$. Note that this estimated height scale is close to the maximum vertical extent of land-breeze circulations found along the southeastern coast of Taiwan during GIMEX (Chien and Lin 2004). Substituting these values into (1) yields an internal Froude number of 0.7. The density-current velocity appears to reasonably predict the observed motion of the front in this case and is consistent with previous observational studies of land-sea-breeze fronts (Schoenberger 1984; Ohara et al. 1989; Wakimoto and Atkins 1994; Carbone et al. 2000). It is noteworthy that the advancing speed of this land-breeze front is much slower than that of midlatitude cool-season land-breeze fronts (Schoenberger 1984; Ohara et al. 1989). The relatively slow seaward speed of the front can be understood as a consequence of an inherently weak temperature gradient between land and ocean, with an average difference of only 1 K, and synoptically prevailing onshore southerly flow present in the lowest 1 km (Fig. 17). As described in section 4b, the low-level onshore flow was evidently intensified by line’s precipitation. This convectively modified onshore flow is expected to further inhibit the seaward penetration of the land-breeze circulation, being limited to a region close to the shore.

5. Conclusions

Examination of Green Island Doppler radar measurements reveal the basic characteristics and structure of offshore convective lines that occurred along the southeastern coast of Taiwan during 11–15 May 1998.
The synoptic environment accompanying these events was relatively undisturbed and featured uniformly prevailing southerly/south-southeasterly winds in the boundary layer with southwesterlies/westerlies aloft. Radar observations from the 5-day period indicate that these convective lines occurred 10–30 km offshore and were characterized by an elongated narrow zone (5–10 km wide) of heavy precipitation approximately parallel to the coast. The lines generally lacked significant movement during their life cycle. The intensity of the lines in terms of their associated radar reflectivities exhibited a pronounced diurnal variation, with a clear tendency to develop (weaken and dissipate) during the nighttime (daytime). These variations were observed to be closely related to the offshore flow developing at night along the southeastern coast.

Detailed analysis of an event on 14–15 May 1998 further showed the important physical link between the offshore flow and the line’s development. Based on these results, Fig. 19 schematically summarizes primary airflow features including the offshore convective line and its vicinity. Low-level southerly inflow entered the system from the east, and was lifted immediately ahead of the seaward extent of the near-coast offshore flow (marked by “L” in Fig. 19). The heaviest precipitation within the line was found to coincide with regions of strong upward motion and low-level convergence, where the southerly onshore flow encountered the cool offshore flow near shore. This offshore flow–induced convergence, given a stable thermodynamic condition in the lowest 1 km in the inflow region, is a crucial low-level forcing that provides additional lifting for the development of moist convection in this case.

Intrusion of environmental dry air into the western part of the line convection was evident, and descending motion was also found in regions of relatively low reflectivity on both sides of the main precipitation/updraft region (Fig. 19). Owing to the line’s precipitation being tilted eastward and confined primarily to the region ahead of the seaward extent of the offshore flow (the warmer inflow side) rather than feeding the cool offshore flow to the west of the line, the intensification of the onshore (offshore) flow due to latent cooling produced by evaporating hydrometeors appeared to be significant (minor). Besides, the lack of consistent upshear tilt of updrafts throughout the storm layer, which is consistent with a strong westerly shear of the line’s environment, is also detrimental to the generation of a strong and large cold pool west of the line capable of organizing the convection into a fast-moving, long-lived system (Rotunno et al. 1988).

The combination of surface and Doppler-radar observations indicated that the leading edge of the land-breeze front moved seaward at a mean speed of 0.7 m s$^{-1}$ and possessed a frontal character with notable discontinuities in surface wind and temperature (rather than pressure and dewpoint temperature). The seaward-moving speed of the land-breeze front is shown to be reasonably consistent with a density-current velocity (Simpson and Britter 1980), a result similar to that found for previously documented land-sea-breeze fronts (Schoenberger 1984; Ohara et al. 1989; Wakimoto and Atkins 1994; Carbone et al. 2000). However, the advancing speed of the present land-breeze front is much slower than that of previously documented mid-latitude cool-season land-breeze fronts (Schoenberger 1984; Ohara et al. 1989). Inherent weak temperature gradients between land and ocean as well as synoptically prevailing onshore flow (i.e., southerly) present in the lowest 1 km (MSL) can both contribute to the slow seaward penetration of the present land-breeze front.

It is worth noting that, as suggested by previous studies of Hawaiian rainbands (Takahashi 1977; Garrett 1980; Raga et al. 1990; Wang and Chen 1998) and other cases of diurnally forced offshore convection (Kousky 1980; Houze et al. 1981), the low-level convergence zone produced as the offshore flow meets the prevailing winds offshore plays a key role in convection initiation. Similarly, our analyses also indicated such convective forcing to be important for the development of the offshore line. The fundamental difference between this and previously documented cases of offshore convection appeared to be the lack of appreciable movement in the present case. As already described, a very slow seaward movement of the land-breeze front limited to a region close to the shore and the characteristic of the line’s airflow and precipitation structure were both essentially unfavorable for the line to move considerably.

Although this study has revealed important character and structure of the offshore convective lines occurring adjacent to the coastline with steep terrain, our understanding of this phenomenon is still incomplete. For example, the specific factors driving the variations of the line’s intensity are so far uncertain. These variations would be probably related to the temporal variation of thermodynamics in the low troposphere found during the study period as well as the increasing influence of the ageostrophic circulations associated with the synoptic mei-yu frontal system as it approached Taiwan particularly after 2000 LST 14 May (e.g., Fig. 4). High-resolution mesoscale models will be required to investigate this problem. Moreover, analyses presented in this paper indicate that the offshore lines occurred when there were prevailing onshore winds at low levels. Based on the Green Island radar observations collected during May–June in 1998 and 1999 (not shown), the
offshore convective lines tend to occur when the low-level synoptic flow was southerly and/or southeasterly (i.e., an onshore synoptic wind). Examination of radar data from whole year of 1998 indicates that the lines occurred more frequently during the mei-yu season, and only very few cases were found in the other season. Based on these observations and the results from the present study, it appears reasonable to conclude that a generally unstable environment during the mei-yu season and an undisturbed onshore synoptic wind should be both favorable for the development of the offshore convective lines. Nevertheless, as shown in Fig. 14b, the line and its vicinity can be sometime characterized by relatively dry conditions (i.e., very weak radar echo return). This implies that, if the offshore lines compose only nonprecipitating clouds they may not be easily captured by routine radar observations. In the future, more complete documentation on the offshore convective lines and their relationship with the ambient environment should rely on a particularly designed radar-observing strategy with higher detection sensitivity and vertical resolution. Furthermore, the cool offshore flow developing at night along the southeastern coast of Taiwan is more likely to be a combination of land breezes and katabatic winds, which, however, cannot be separated in our available observations. Hence, the relative importance of land–sea thermal contrast versus mountain-induced circulations on influencing the kinematics and thermodynamics of the offshore flow is also uncertain in this study. The significance of along-coast variation of landmass on diurnally triggered precipitation has been generally recognized previously (Purdom 1976; Baker et al. 2001). Our results also indicate that an earlier initiation of offshore flow and precipitation was observed off a more northern coastal region immediately upstream of the Coastal Range, as described in section 4a. This suggests that the development of the offshore convective line particularly during the early stage of its evolution was related to the along-coast variation of terrain features. Nevertheless, the lack of adequate observations in the coastal zone and over the mountain slopes prevents explicit addressing of this issue. Future detailed observations that include both mountainous inland regions and offshore regions, plus numerical simulations, are required to provide a more comprehensive description of offshore convection along the southeastern coast of Taiwan and to further improve our understanding of its underlying dynamical processes.

Acknowledgments. Green Island radar data used in this study were provided by the Weather Wing of the Chinese Air Force. The radar processing software utilized in this study was in part provided by Dr. Feng Lei. The authors thank Mr. Chin-Min Chou for providing real-time images of Green Island radar from 1998, which were helpful for the selection of our studied cases; Dr. Jing-Shan Hong and De-En Lin for assistance in the production of the synoptic analysis map; and Ming-Jung Yang and Jiang-Shang Tseng for assistance in gathering surface data. We thank Profs. George Tai-Jen Chen and Yi-Leng Chen for their helpful comments during the preparation of the manuscript. We also thank three anonymous reviewers for their constructive and insightful comments on the manuscript, as well as Mrs. Candace Gudmundson for proofreading the manuscript. This research support was provided by the National Science Council of the Republic of China under Grants NSC92-2119-M-034-002, NSC93-2111-M-034-001, and NSC93-2111-M-002-015-AP2.

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