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Investigation of a heavy rainfall event over southwestern Taiwan associated with a subsynoptic cyclone during the 2003 Mei-Yu season

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ABSTRACT

The objective of this study is to perform observational data analyses, including European Centre for Medium-Range Weather Forecasts (ECMWF) data, satellite imagery, radar reflectivity, and rainfall data, and numerical simulations with the Weather Research and Forecast (WRF) model to investigate both the synoptic and mesoscale processes responsible for causing the heavy rainfall event which produced up to 379.5 mm over southwestern Taiwan on 7 June 2003. We found that an 850 hPa subsynoptic cyclone, composed of both a low-pressure center and a vortex, formed over the eastern Tibetan Plateau and moved with a 500 hPa shortwave trough toward a wind shear zone over southeastern China in the early morning of 7 June. The wind shear zone was generated by a southwesterly monsoonal flow and a northeasterly flow associated with a high pressure in eastern China. The intensifying 850 hPa subsynoptic cyclone served as a precursor of the heavy rainfall episode in Taiwan. The 850 hPa subsynoptic cyclone extended downward to form a surface subsynoptic cyclone over the southeastern coast of China by coupling the ascending motions associated with the 500 hPa shortwave trough and the 850 hPa subsynoptic cyclone. The mesoscale convective system associated with this surface subsynoptic cyclone migrated from southeastern China to the southwestern Taiwan Strait and then toward southwestern Taiwan. Meanwhile, the speed of the 850 hPa low-level jet on the southern side of the subsynoptic cyclone exceeded 20 m s^{-1} over the southern Taiwan Strait. This jet then served as a conveyor belt of the moist airstream and enhanced the inland-moving convection over the mountain slopes. In addition, the low-level convergence resulted from the confluence of flow due to flow deflection over southern Taiwan topography also facilitated rainfall there.

1. Introduction

During the Mei-Yu season (mid-May to mid-June), which is one of the major rainfall periods in Taiwan (Chen and Chen, 2003), extremely heavy rainfall is frequently recorded over southwestern Taiwan (south of 23.5°N and west of Central Mountain Range (CMR)) (Chen et al., 2007). Extremely heavy rainfall here is defined as a daily rainfall accumulation greater than 130 mm and an hourly rainfall rate exceeding 15 mm recorded at a minimum of one rainfall observation site (Wang et al., 1985). The criterion of the extremely heavy rainfall is used by the forecasters of the Central Weather Bureau (CWB, all acronyms are defined in Table 1) of Taiwan. Mesoscale convective systems (MCSs) embedded in the southwesterly monsoonal flow and Mei-Yu fronts are responsible for producing the majority of rainfall (Chen and Chen, 2003) that can cause localized heavy rainfall (Chen et al., 2007) under suitable large-scale conditions (Chen and Li, 1995). Additionally, orographic effects are also important for generating or intensifying heavy rainfall over southwestern Taiwan (Chen et al., 2005, 2007; Lin et al., 2001) because approximately two-thirds of Taiwan is covered by mountains (Fig. 1).

Previous studies on the extremely heavy rainfall events over southwestern Taiwan during the Mei-Yu season show

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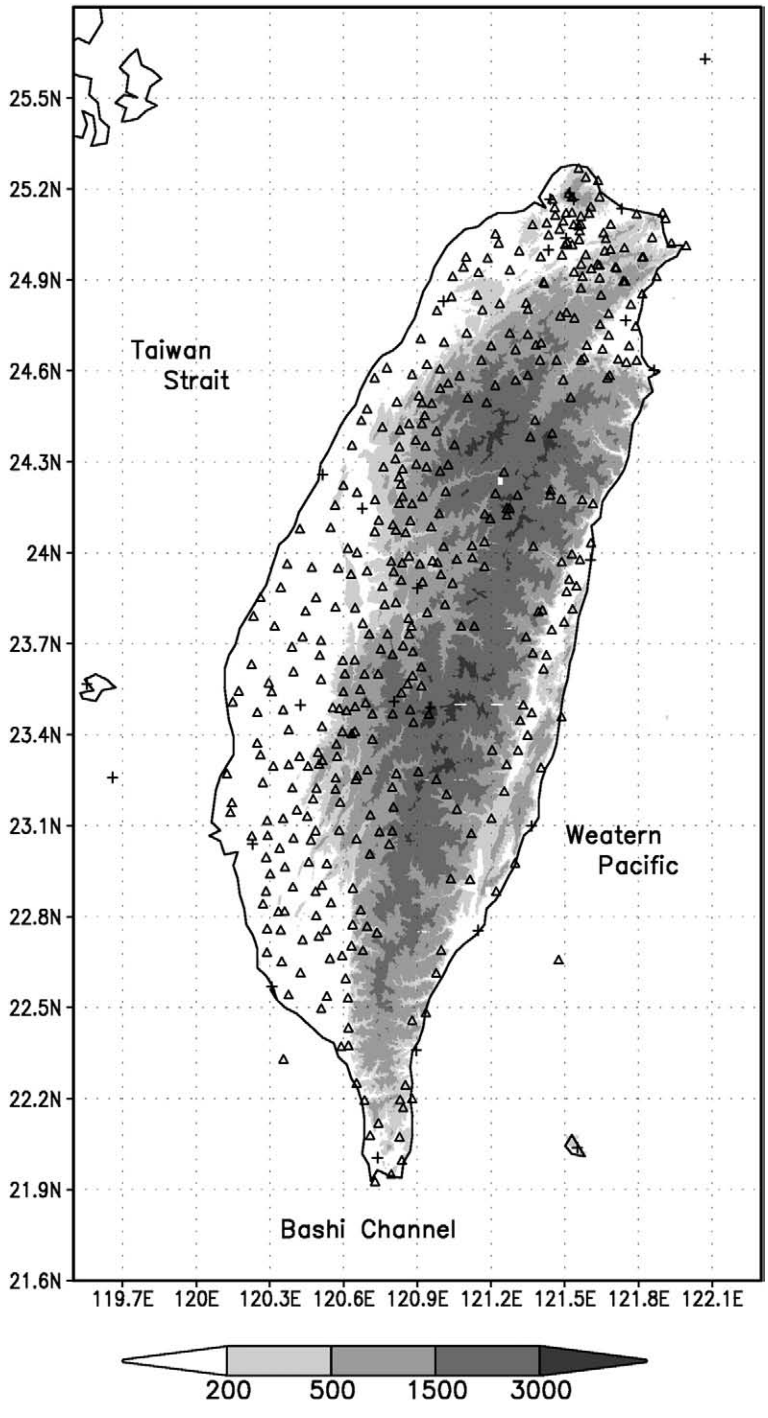

Fig. 1. Distribution of rainfall stations in Taiwan from the Automatic Rainfall and Meteorological Telemetry System (ARMTS, triangles) and twenty-five conventional stations (crosses). The gray scale shows terrain elevations in meters.

that the disturbances that cause extremely heavy rainfall originate either from the ocean near the southwest coast (Chen et al., 2005) or from the southern Taiwan Strait and northern South China Sea (Chen et al., 2005; Zhang et al., 2003). In this study, we investigate an extremely heavy rainfall event over southwest Taiwan, which appears to be associated with a subsynoptic cyclone (containing a low-pressure center and a vortex) migrating from the southeastern coast of China. This type of vortex frequently occurs in the eastern part of the Tibetan Plateau during spring and summer and is named the southwest vortex (Tao and Ding, 1981). Normally, these vortices develop in the planetary boundary layer and extend to 2 or 3 km vertically. Some of them evolve into low-pressure disturbances, which produce heavy rainfall over eastern China (Tao and Ding, 1981). However, in the literature, no study shows that the southwest vortex affects the heavy rainfall over the southwestern Taiwan during Taiwan Mei-Yu period.

Many studies of the southwest vortex suggested that terrain effects are important for initiating the southwest vortex (e.g., Chang et al., 2000; Yasunari and Miwa, 2006). In addition, it was noted that upper- and middle-level troughs play an important role in the development of the southwest vortex (e.g., Chang et al., 2000). Prior to the seasonal transition in mid-June, Chen et al. (1994), Chen and Chen (1995), and Chen and Tseng (2000) stressed that the development of low pressure at low levels over the eastern side of the Tibetan Plateau is associated with the passage of the high- or mid-level trough.

In this study, we investigate an extremely heavy rainfall event, which appears to be associated with a surface subsynoptic cyclone that migrated from the southeastern coast of China to southwestern Taiwan with a maximum daily accumulated rainfall of 379.5 mm at station C1R140 (120.68°E, 22.69°N). We will show that an 850 hPa subsynoptic cyclone over the southeastern China coast served as a precursor for inducing the heavy rainfall event that occurred on 7 June 2003 over southwestern Taiwan. A surface subsynoptic cyclone over the southeastern China coast was generated on the southeastern side of the 850 hPa subsynoptic cyclone when it was coupled with an approaching 500 hPa shortwave trough. This surface subsynoptic cyclone intensified over the Taiwan Strait at 0800 LST (0000 UTC) 7 June. We will further demonstrate that the mesoscale convective system associated with the surface subsynoptic cyclone, which moved into southwestern Taiwan during the early morning of June 7, interacted with the mountains and subsequently triggered this heavy rainfall event.

The objective of this study is to perform observational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) data, satellite imagery, radar reflectivity, and rainfall data for the synoptic and mesoscale processes to support the importance of the above two mechanisms. The mesoscale process associated with the development of the heavy rainfall event and the orographic effects on the enhancement of accumulated rainfall are examined by the Weather Research and Forecast (WRF, Skamarock et al., 2005) model.

2. Observational analysis

2.1. Description of the dataset

Several observational datasets are used to characterize the heavy rainfall episode observed over southwestern Taiwan and to initialize and verify the results of WRF in this study. The dataset used are: (1) ECMWF/Tropical Ocean Global Atmosphere (TOGA) data utilizing 1.125°×1.125° latitude–longitude grid spacing and 6 h time interval for the initialization of the WRF. (2) Radar images with 2-km grid spacing from the CWB of Taiwan, which are available every hour. The images of the maximum reflectivity (in dBZ) in the vertical column are used to trace the most intense convective systems over the southern Taiwan Strait and southwestern Taiwan. (3) Hourly rainfall data from 397 Automatic Rainfall and Meteorological Telemetry System (ARMTS, Chen et al., 2007) around Taiwan (Fig. 1) is used to examine the spatial and temporal characteristics of the observed rainfall.

2.2. Synoptic overview

At 0800 LST 7 June, a 300 hPa jet streak associated with the low-pressure center over the Korean Peninsula extended from the East China Sea to southern Japan (Fig. 2a). Taiwan was located beneath the southern jet streak entrance quadrant where upward motion would have existed. Upward motion existed over the Taiwan Strait and Taiwan in the current case (Fig. 2a). A 500 hPa shortwave trough migrating from the southeast coast of China at 0200 LST was located over the Taiwan Strait (Fig. 2b and c). At 850 hPa, a subsynoptic cyclone, “L1” was located in proximity to a wind shear zone in southeastern China (Fig. 2b). The wind shear zone was produced by the juxtaposition of a southwesterly monsoonal flow and a northeasterly flow from eastern China associated with a high pressure over east China. The 850 hPa subsynoptic cyclone was strengthened over the Taiwan Strait and Taiwan as it existed below a 500 hPa shortwave trough. As a result, the west-southwesterly low-level jet (LLJ) was strengthened to 20 m s^{-1} over the southern Taiwan Strait and eastern Taiwan. The surface subsynoptic cyclone that originally formed to the south of the Mei-Yu front over the southeast coast of China beneath the 500 hPa shortwave trough at 0200 LST (Fig. 2c) migrated from the southeast coast of China toward the ocean near the western coast of Taiwan at 0800 LST (Fig. 2c). The Mei-Yu front extended from central Taiwan through the surface subsynoptic cyclone to southern China. Along and ahead of the Mei-Yu front, clouds extended from southern China to southern Taiwan (Fig. 2d).

Fig. 3 shows the temporal change of the profiles of the wind, relative humidity, and equivalent potential temperature near the southern Taiwan Strait just upstream of southwestern Taiwan, occurred before and during the heavy

Table 1
List of acronyms.

Acronym	Meaning
ARMTS	Automatic Rainfall and Meteorological Telemetry System
CMR	Central Mountain Range of Taiwan
CWB	Central Weather Bureau
ECMWF	European Centre for Medium-Range Weather Forecasts
LLJ	Low-level jet
MCS	Mesoscale convective system
MSW2	Another simulated 500 hPa shortwave trough over the eastern slope of the Yun-Kuei Plateau (Fig. 6a)
NT	Sensitivity experiment without Taiwan topography
SL	The surface subsynoptic cyclone system moved out of the China coast
SL1	Another surface subsynoptic cyclone simulated in the control run
SLN	Surface subsynoptic cyclone simulated in case NT
SW	A 500 hPa shortwave trough
TOGA	Tropical Ocean Global Atmosphere
WRF	Weather Research and Forecast

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rainfall episode as the 500 hPa shortwave trough approached. Prior to 0800 LST 6 June, the southwesterly flow prevailed over the Taiwan Strait accompanying the possible existence of convective instability, which existed below 700 hPa (where $\partial\theta_e/\partial z<0$), similar to that found in Chen and Chen (2003). After 0800 LST 6 June, the low-level wind, moisture, and equivalent potential temperature began to increase. By 2000 LST 6 June, an 850 hPa LLJ (exceeding 12.5 m s^{-1}) formed over the southern Taiwan Strait (Fig. 3). Concurrently, relative humidity and low-level equivalent potential temperature increased dramatically. The low-level equivalent potential temperature peaked at 0200 LST 7 June (Fig. 3) when the 500 hPa shortwave trough reached the southeast China coast and the southwestern Taiwan Strait (Fig. 2c). When the 500 hPa shortwave trough reached the central Taiwan Strait at 0800 LST June 7 (Fig. 2b), the LLJ increased to 21 m s^{-1} (Fig. 3). In conjunction with the strengthening LLJ, the increase of low-level equivalent potential temperature and relative humidity during the evening of 6 June and the early morning of 7 June enhanced the convective activity over the southern Taiwan Strait.

2.3. Convection over the southern Taiwan Strait and southwestern Taiwan

As the convective activity associated with the 850 hPa subsynoptic cyclone increased over the northern South China Sea and the western Taiwan Strait during the evening of 6 June (not shown), radar echoes over the southeastern China coast and western Taiwan Strait moved eastward toward southern Taiwan at 2100 LST 6 June 2003 (Fig. 4a). An intense MCS (with the maximum radar reflectivity exceeding 40 dBZ) was over the southern Taiwan Strait (Fig. 4a). At 0200 LST 7 June (Fig. 4b), this strong MCS moved inland. Consequently,

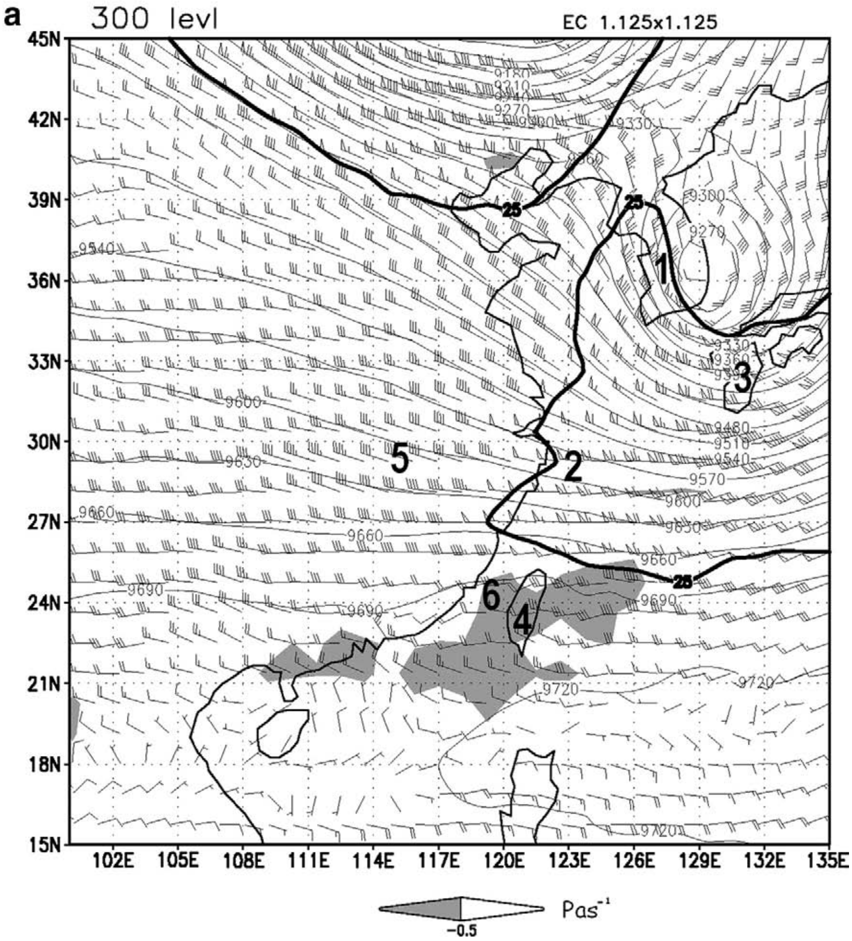


Fig. 2. (a) 300 hPa synoptic analysis at 0800 LST 7 June 2003 from the ECMWF/TOGA data including heights (solid lines, 30 gpm contour interval) and winds (a full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively; also used for other figures). The heavy solid line encloses an area with wind speed exceeding 25 m s^{-1}. The shaded area represents ascending motion greater than 0.5 Pa s^{-1}. Number 1 through 6 denotes the Korean Peninsula, East China Sea, southern Japan, Taiwan, China, and the Taiwan Strait, respectively. (b) Same as (a) but for the 850 hPa level. L1 denotes the subsynoptic cyclone. The zigzag line represents the LLJ axis with wind speed exceeding 12.5 m s^{-1}. The heavy solid line represents the 500 hPa shortwave trough (SW). (c) Surface synoptic analysis at 0800 LST 7 June 2003 from ECMWF/TOGA data including pressures (solid lines, contour interval is 2 hPa) and winds. The heavy solid line denotes the Mei-Yu front. SL denotes the surface subsynoptic cyclone over the central Taiwan Strait. A cross and a heavy dashed line represent the surface subsynoptic cyclone formed over the southeastern coast of China and the location of a 500 hPa shortwave trough (SW) at 0200 LST. (d) IR imagery at 0800 LST 7 June 2003.

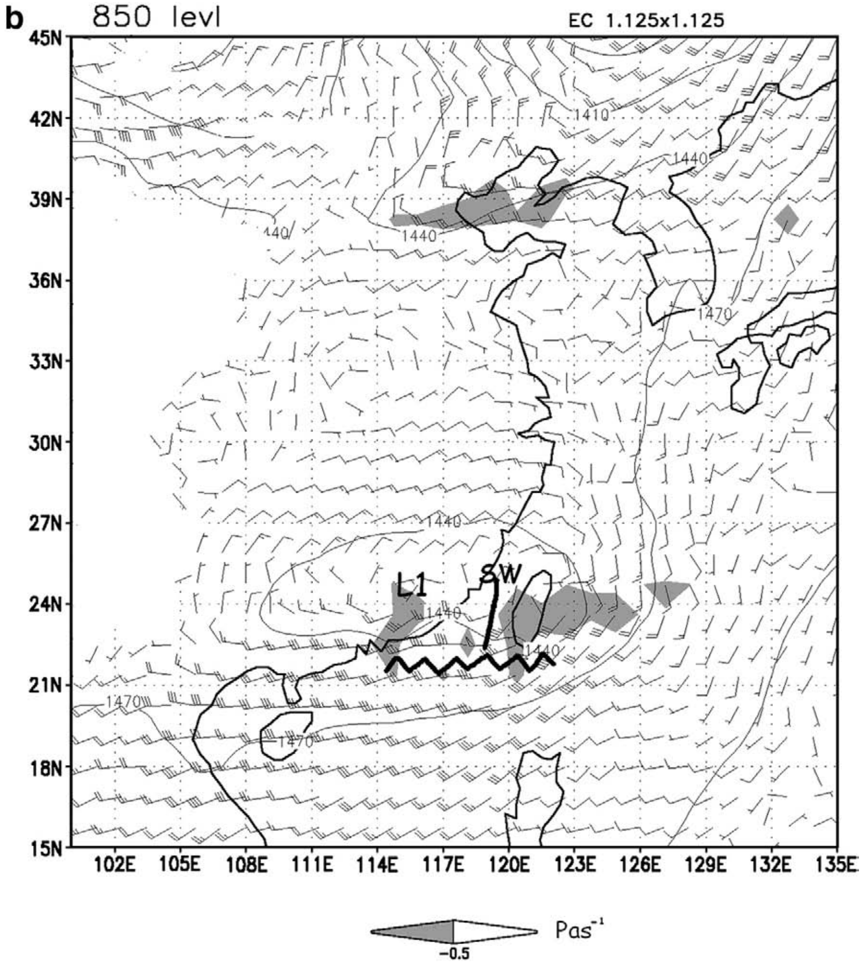


Fig. 2 (*continued*).

rainfall began to increase over southwestern Taiwan during the period 0100–0300 LST (Fig. 5a). At 0200 LST, this strong MCS merged with the surface subsynoptic cyclone (Fig. 2c) over the western Taiwan Strait (Fig. 4b). Convection intensified dramatically after the merging of these two systems as revealed by the radar echoes while they moved toward southern Taiwan. At 0400 LST (Fig. 4c), the merged MCS made landfall on the southwestern coast of Taiwan. Radar echoes intensified while the merged MCS moved toward the mountains (not shown). Consequently, during the periods 0400–0600 and 0700–0900 LST, rainfall increased significantly (Fig. 5b and c). After 0900 LST, radar echoes indicate that the rainfall rate decreased (not shown). This demonstrates that no intense convective system moved inland. Hence, areas subject to the highest rainfall over southwestern Taiwan was likely related to the inland movement of the merged MCS and the surface subsynoptic cyclone.

The accumulated daily rainfall shows that the rainfall stations with 130 mm of accumulated rainfall covered almost all of southwestern Taiwan (Fig. 5d). The region with high accumulated rainfall extended from the coastal areas near Tainan and Kuohsiung eastward toward the slopes and mountains, respectively. Over southwestern Taiwan, 88% of the 104 rainfall stations registered accumulated rainfall over 130 mm day^{-1} on June 7.

A maximum accumulated rainfall of 379.5 mm day^{-1} was recorded at station C1R140 over the mountains (Fig. 5d). It appears that the heavy rainfall over the slopes (Fig. 5d) was likely produced by orographic lifting of a fast-moving moist airstream (Fig. 3) which satisfied two common ingredients for heavy orographic rainfall (Lin et al., 2001). The rainfall over the coastal area was enhanced by the interaction between the off-shore flow and prevailing monsoonal flow similar to that found in Chen and Nash (1994). Over southwestern Taiwan, southwesterly onshore flow was observed over the southern tip of the island at 0200 and 0500 LST and easterly off-shore flow was observed at plains stations (Fig. 5a and b). The convergence associated with the onshore flow and the off-shore flow caused by orographic blocking and land–sea temperature contrast likely enhanced the rainfall in the plains and coastal areas (Fig. 5d).

In summary, the above observational analysis shows that the heavy rainfall over southwestern Taiwan on 7 June 2003 was produced by the inland movement of an MCS from the southern Taiwan Strait. The MCS then merged with a surface

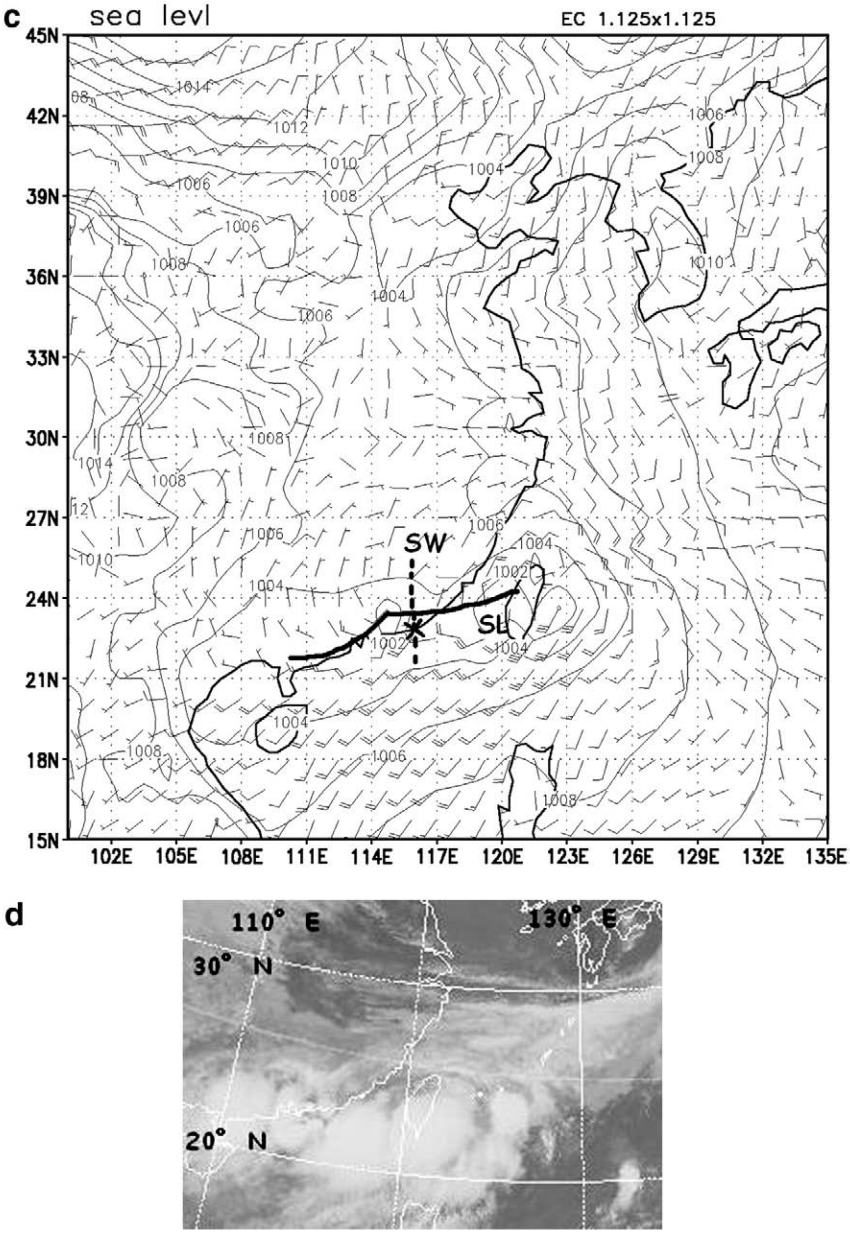


Fig. 2 (*continued*).

subsynoptic cyclone over the southeastern China Coast. The surface subsynoptic cyclone occurred on the southeastern side of an 850 hPa subsynoptic cyclone in southeastern China apparently caused by a 500 hPa shortwave trough over the southeastern China coast and on the southeastern side of the 850 hPa subsynoptic cyclone in the early morning of 7 June. The 500 hPa shortwave trough is an important ingredient conductive to heavy orographic rain (Lin et al., 2001), such as the severe flash floods in Madison County, VA, Fort Collins, CO, Rapid City, SD, and Big Thompson Canyon, CO (Pontrelli et al., 1999). The circulations associated with both the 850 hPa and surface subsynoptic cyclone strengthened the southwesterly monsoonal flow and transported the moisture into southern Taiwan. The increase of moisture contributed to the increase of the low-level convective instability and facilitated the development of the high rainfall event. Taiwan's topography enhanced rainfall over southwestern Taiwan.

3. Numerical simulations

3.1. Numerical experiment design

The WRF model was employed to help understand the details of the dynamics and physical processes responsible for the high rainfall on 7 June 2003. In order to better resolve the movement of the 500 hPa shortwave trough and 850 hPa

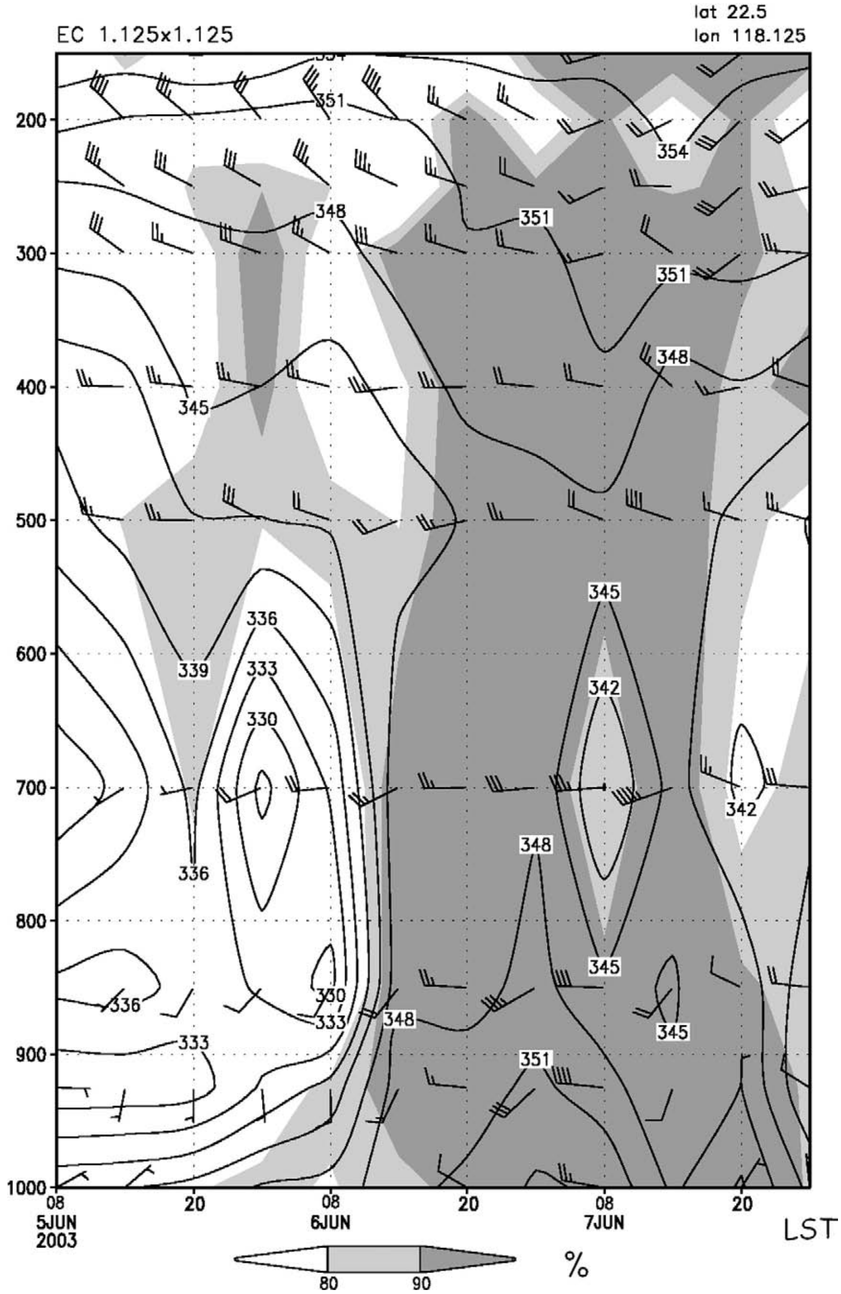


Fig. 3. The temporal variation of the profiles of wind, equivalent potential temperature (contour interval is 3 K), and relative humidity (greater than 90% in dark, between 90% and 80% in gray, less than 80% in white) over the southern Taiwan Strait at 22.5°N and 118.125°E during the period of 0800 LST 5 June to 0200 LST 8 June.

subsynoptic cyclone from southwestern China to southeastern China coast as well as the surface subsynoptic cyclone and rainfall over the Taiwan, nested grids were used at horizontal resolutions of 36 km, 12 km, 4 km and 1.33 km. All domains were comprised of 31 vertical levels from the surface to 50 hPa. The moisture processes included the subgrid-scale convective parameterization of Grell (1993) in Domains 1 and 2 and the grid-resolvable WSM 5-class microphysics scheme (Hong et al., 2004). Planetary boundary layer processes were represented by the YSU PBL parameterization (Hong et al., 2006). The model was initialized and lateral boundary conditions derived from the ECMWF/TOGA analyses at 0800 LST (0000 UTC) 5 June 2003 and integrated for 66 h. In order to examine the Taiwan orographic effects on the occurrence of the heavy rainfall over southwestern Taiwan, we performed a sensitivity test without Taiwan's topography (NT) on 12-, 4-, and 1.33-km grid spacing simulations, while keeping everything else identical to the control run. The procedure of the setup of topography in the NT is similar to that in Chiao et al. (2004).

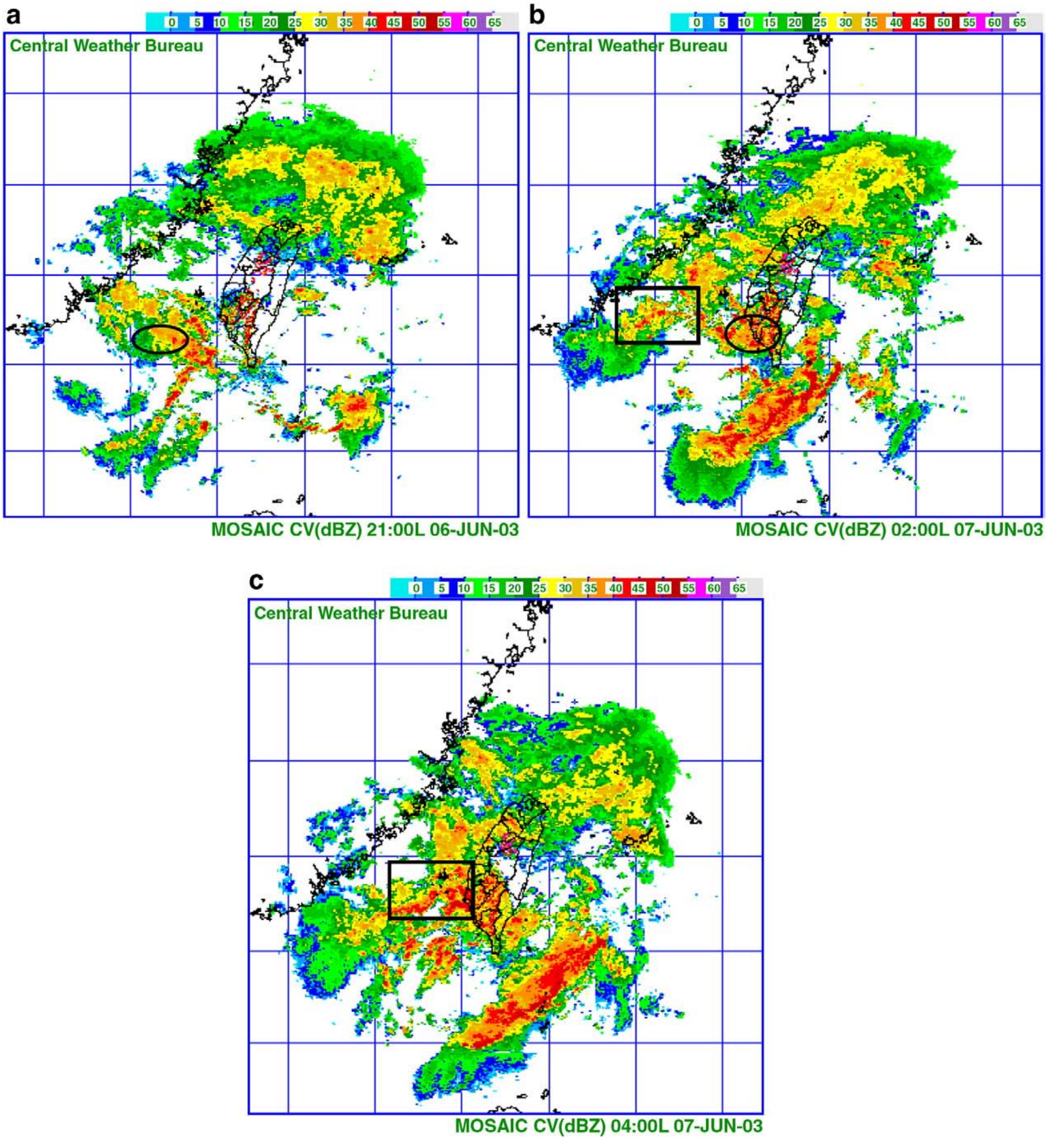
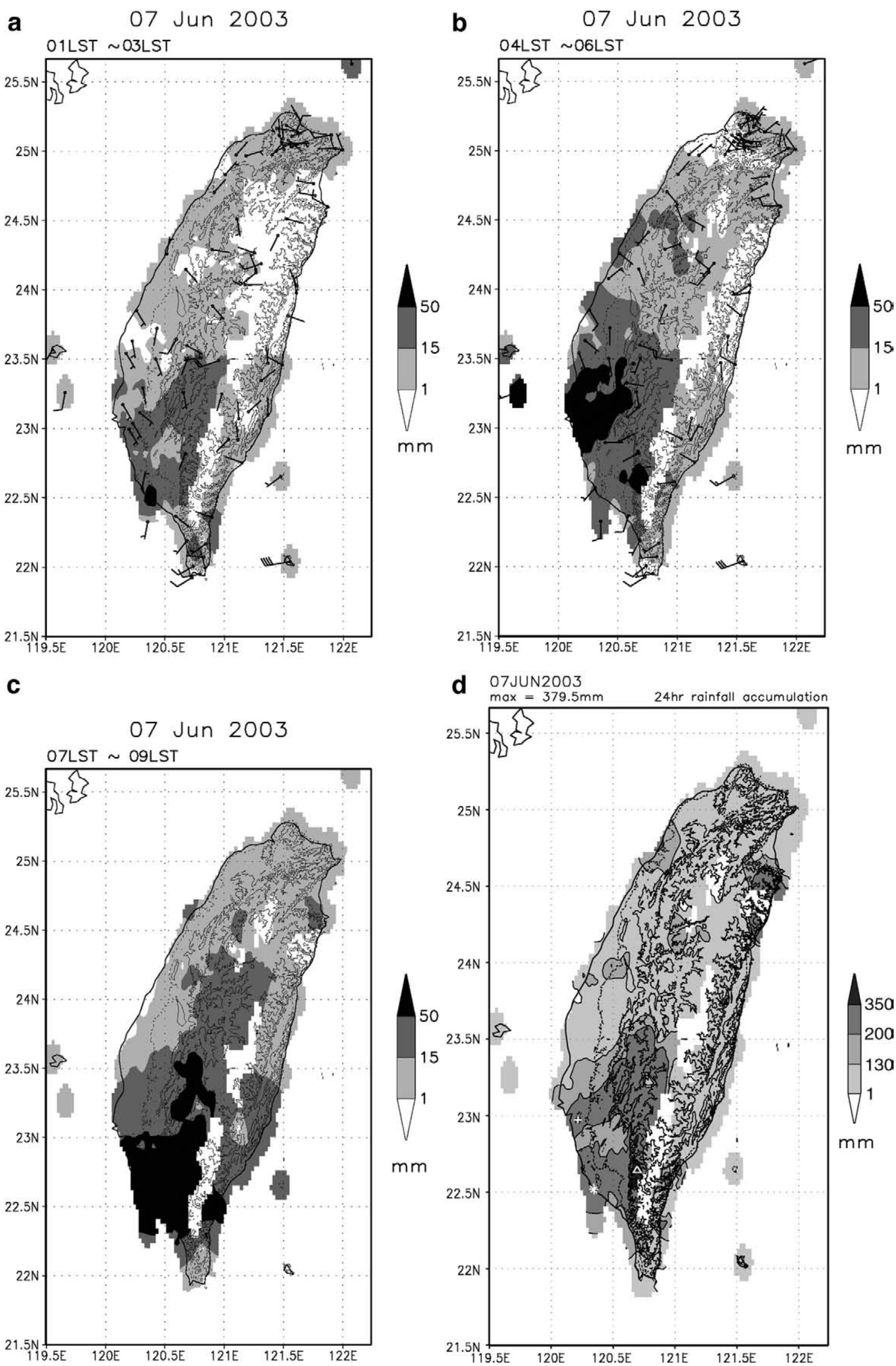


Fig. 4. The maximum radar reflectivity in a vertical column composted by Central Weather Bureau radars: (a) 2100 LST 6 June. (b) 0200 LST 7 June and (c) 0400 LST 7 June. The ovals in (a) and (b) denote the mesoscale convective system (with maximum radar reflectivity exceeding 40 dBZ) from the southern Taiwan Strait to southern Taiwan. The squares in (b) and (c) denote the movement of convection with maximum radar reflectivity exceeding 40 dBZ from southwestern Taiwan Strait to southern Taiwan.

3.2. Simulations of large-scale flow and weather systems

At 0800 LST 5 June, a 500 hPa shortwave trough (SW) was over the eastern slope of Tibet (Fig. 6a) underneath the 300 hPa westerly flows (not shown). Below the 500 hPa shortwave trough, an 850 hPa subsynoptic cyclone (L1) was over the eastern slope of Tibet (Fig. 6a). Over the eastern slope of the Yun-Kuei Plateau in southwestern China, another 500 hPa

Fig. 5. (a) Accumulated rainfall during 0100–0300 LST 7 June 2003. The magnitude is shown by the gray scale in mm. Surface winds derived from conventional stations and some ARMTS (Fig. 1) at 0200 LST 7 June. The terrain elevations are 20 m (dotted line) and 200, 500, and 1500 m (solid lines), respectively. (b) Same as (a) but the accumulated rainfall is for 0400–0600 LST and surface winds are for 0500 LST. (c) The accumulated rainfall during 0700–0900 LST. (d) The accumulated daily rainfall on 7 June 2003. The magnitude is shown by the gray scale in mm. Tainan, Kuohsiung, and station C1R140 are represented by a cross, an asterisk, and a triangle, respectively. The terrain elevations are 20 m (dotted line) and 200, 500, and 1500 m (solid lines), respectively.


a
07 Jun 2003
01LST ~03LST
b
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c
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max = 379.5mm
24hr rainfall accumulation
50
15
1
mm
350
200
130
1
25.5N
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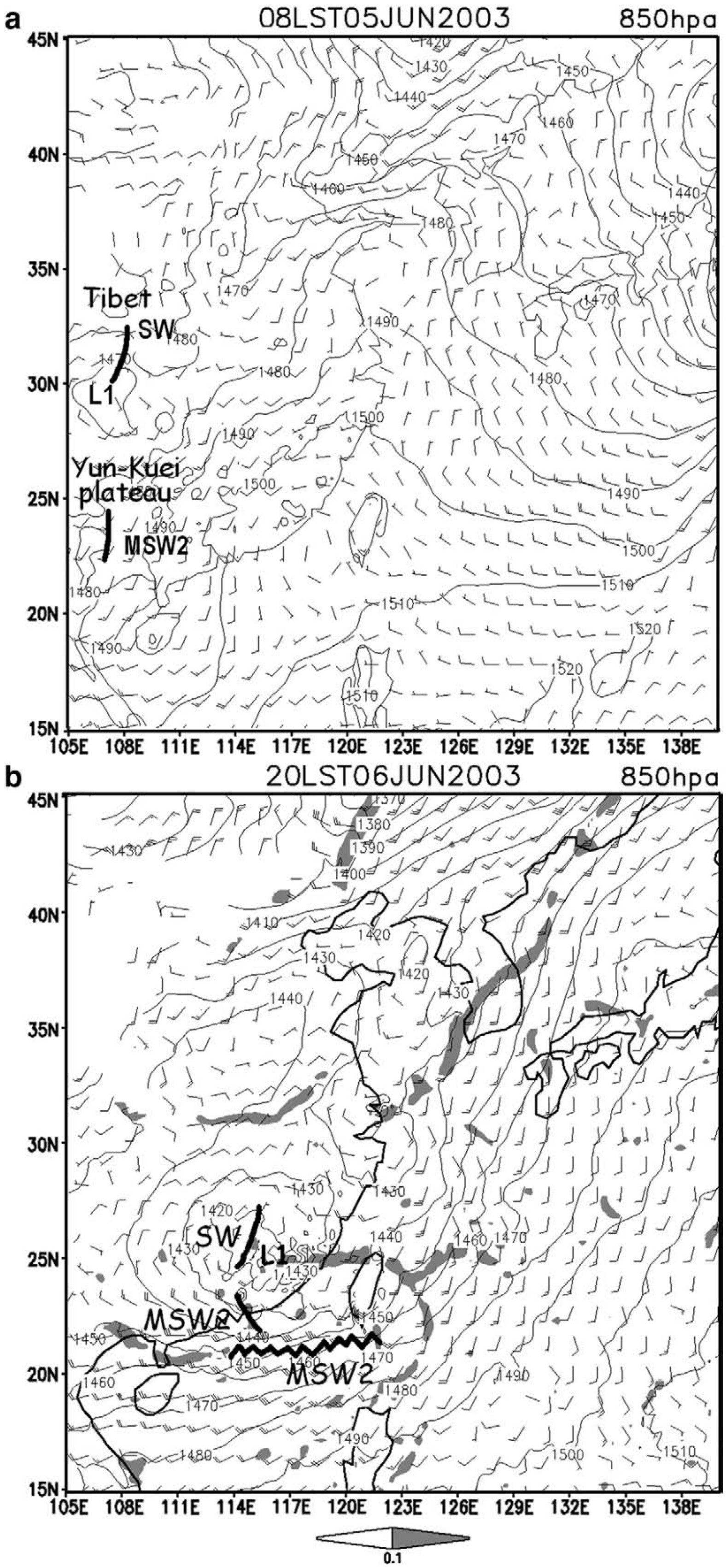

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shortwave trough (MSW2) developed (Fig. 6a). This numerically simulated 500 hPa shortwave trough (MSW2) was not evident in the observed analysis (not shown). The 850 hPa subsynoptic cyclone (L1) moved southeastward to southeastern China at 2000 LST 6 June (Fig. 6b) and intensified beneath the 500 hPa shortwave trough (SW). Meanwhile, the 850 hPa subsynoptic cyclone was located over a wind shear zone that was caused by a northeasterly flow associated with a high pressure in northern China and a southwesterly monsoonal flow. A simulated LLJ was present in the southern Taiwan Strait and northeastern South China Sea. This wind pattern is similar to that of the observed flow at 2000 LST 6 June (Peng, 2006) and at 0800 LST (Fig. 2b). Another simulated 500 hPa shortwave trough (MSW2) arrived over the southern China coast at this time (Fig. 6b).

In order to investigate the formation mechanism of the surface subsynoptic cyclone at 0200 LST 7 June as indicated by the observations (Fig. 2c), the simulation results from a 12 km grid spacing simulation is performed. At 500 hPa, two shortwave troughs SW and MSW2 (Fig. 6a) merged to become a shortwave trough over the southeastern China coast and the southwestern Taiwan Strait (Fig. 7a). The location of the simulated shortwave trough was similar to that observed (Fig. 2c). The ascending motion associated with the simulated shortwave trough was over the southeastern coast and the western Taiwan Strait (Fig. 7a) where active convection was observed (Fig. 4b). Another area of upward motion on the 500 hPa surface extended southwestward from northern Taiwan to southeastern China (Fig. 7a) and was associated with the 850 hPa wind shear zone (Fig. 7a) and the Mei-Yu front where clouds were present (Fig. 7b). At 850 hPa, over the southeastern China coast and the western Taiwan Strait (Fig. 7a), the upward motion associated with the subsynoptic cyclone was beneath the 500 hPa short wave trough (Fig. 7a). Below the 850 hPa strong upward motion, two surface low-pressure centers were simulated over southeastern China (Fig. 7b). One was below the center of the 850 hPa subsynoptic cyclone (Fig. 7b), while the other surface subsynoptic cyclone (Fig. 7b) with cloud water was underneath the 500 hPa shortwave trough (Fig. 7a) over the coastal area of China. The location of the simulated surface subsynoptic cyclone over the China coast was similar to the observed (Fig. 2c). The interaction between the 500 hPa shortwave trough and the 850 hPa subsynoptic cyclone facilitated the generation of a surface low pressure. Similar to the observations (Fig. 3), the magnitude of 850 hPa LLJ increased to at least 17.5 m s^{-1} over the southern Taiwan Strait just on the upstream side of southwestern Taiwan (Fig. 7a).

At 0800 LST 7 June, the 500 hPa shortwave trough moved to the central Taiwan Strait (Fig. 7c) and the ascending motions were over the Taiwan Strait and Taiwan. In conjunction with the eastward movement of the 500 hPa shortwave trough, the 850 hPa subsynoptic cyclone over the China coast 6 h earlier moved to the Taiwan Strait and intensified (Fig. 7c). The magnitude of the simulated LLJ increased to 25 m s^{-1} over the southern Taiwan Strait (Fig. 7c), stronger than that observed 21 m s^{-1} (Fig. 3). At the surface along the Mei-Yu front, the subsynoptic cyclone was strengthened to 998 hPa and located underneath the 500 hPa shortwave trough and the 850 hPa subsynoptic cyclone in the central Taiwan Strait (Fig. 7d). The intensity of the simulated surface subsynoptic cyclone was stronger in the 12 km grid spacing than that observed at 1001 hPa (Fig. 2c). The simulated results illustrate that the 500 hPa shortwave trough and 850 hPa subsynoptic cyclone play an important role for producing the 850 hPa LLJ and surface subsynoptic cyclone.

3.3. Simulated evolution of mesoscale convection

In order to better illustrate the evolution of the mesoscale convection with the surface subsynoptic cyclone, the inland movement of the coupling of the simulated MCS and the surface subsynoptic cyclone will be illustrated by using the 4 km grid spacing simulation. At 0200 LST 7 June, clouds associated with the surface subsynoptic cyclone (SL) were over the southeastern China coast and the western Taiwan Strait (Fig. 8a). The southwesterly flow transported high equivalent potential temperature air to the Taiwan Strait (Fig. 9a). Clouds also occurred over the central Taiwan Strait in association with another simulated surface subsynoptic cyclone-1 (SL1). Clouds associated with the Mei-Yu front stretched from northern Taiwan westward to the southeastern China coast (Fig. 8a). Satellite imagery (not shown) and radar reflectivity at 0200 LST (Fig. 4b) also show that clouds and precipitation were over the northern, central, and western Taiwan Strait and northern Taiwan. The simulated rainfall increased over the central and southwestern Taiwan Strait (Fig. 9a). The southwesterly flow over the Taiwan Strait converged with a southerly flow over the western Taiwan coast and nearby ocean resulting from orographic blocking (Fig. 8a). In addition, similar to the observed off-shore flow (Fig. 5a), the simulated low-level off-shore flow/land-breeze, which was due to the virtual potential temperature contrast between the coastal areas and the nearby ocean (Fig. 10) along an east–west cross section passing through the Tainan area (Fig. 9a), converged with the prevailing flow over the coastal areas. This flow deflection also strengthened the confluence over the southwestern coastal areas (Fig. 8a) and the accompanying upward motion (Fig. 10). As a result, the simulated rainfall near Tainan area was enhanced (Fig. 9a). Over the mountainous area, the prevailing southwesterly flow (Fig. 7a) strengthened the simulated rainfall (Fig. 9a).

At 0800 LST, while the Mei-Yu front moved southward to the central Taiwan Strait, the surface SL1 moved toward the northwest coast of Taiwan (Fig. 8b) and enhanced the rainfall there (Fig. 9b). Meanwhile, the surface SL moved out of the China coast to the central Taiwan Strait and along the Mei-Yu front (Fig. 8b) as observed (Fig. 2c). Regions of high cloud water (Fig. 8b) and precipitation (Fig. 9b) associated with the

Fig. 6. (a) The 850 hPa initial heights (solid lines, 10 gpm contour interval) and winds at 0800 LST 5 June used in the 36 km grid spacing simulation. Heavy solid lines represent the 500 hPa shortwave troughs SW and MSW2, respectively. L1 denotes the subsynoptic cyclone. (b) The 850 hPa simulated heights (solid lines, 10 gpm contour interval) and winds at 2000 LST 6 June in the 36 km grid spacing simulation. Areas of 850 hPa ascending motion greater than 0.1 m s^{-1} are shaded. L1 represents the subsynoptic cyclone. The zigzag line and heavy solid lines represent the 850 hPa LLJ axis with wind speed exceeding 12.5 m s^{-1} and the shortwave troughs SW and MSW2, respectively.

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surface SL moved from the southern Taiwan Strait into southwestern Taiwan during the period in between 0600 and 0900 LST (Fig. 9b). Again, the southwesterly flow over Taiwan Strait converged with the southerly flow over the western Taiwan coast and nearby ocean resulting from orographic blocking (Fig. 8b). As a result, the simulated rainfall near the

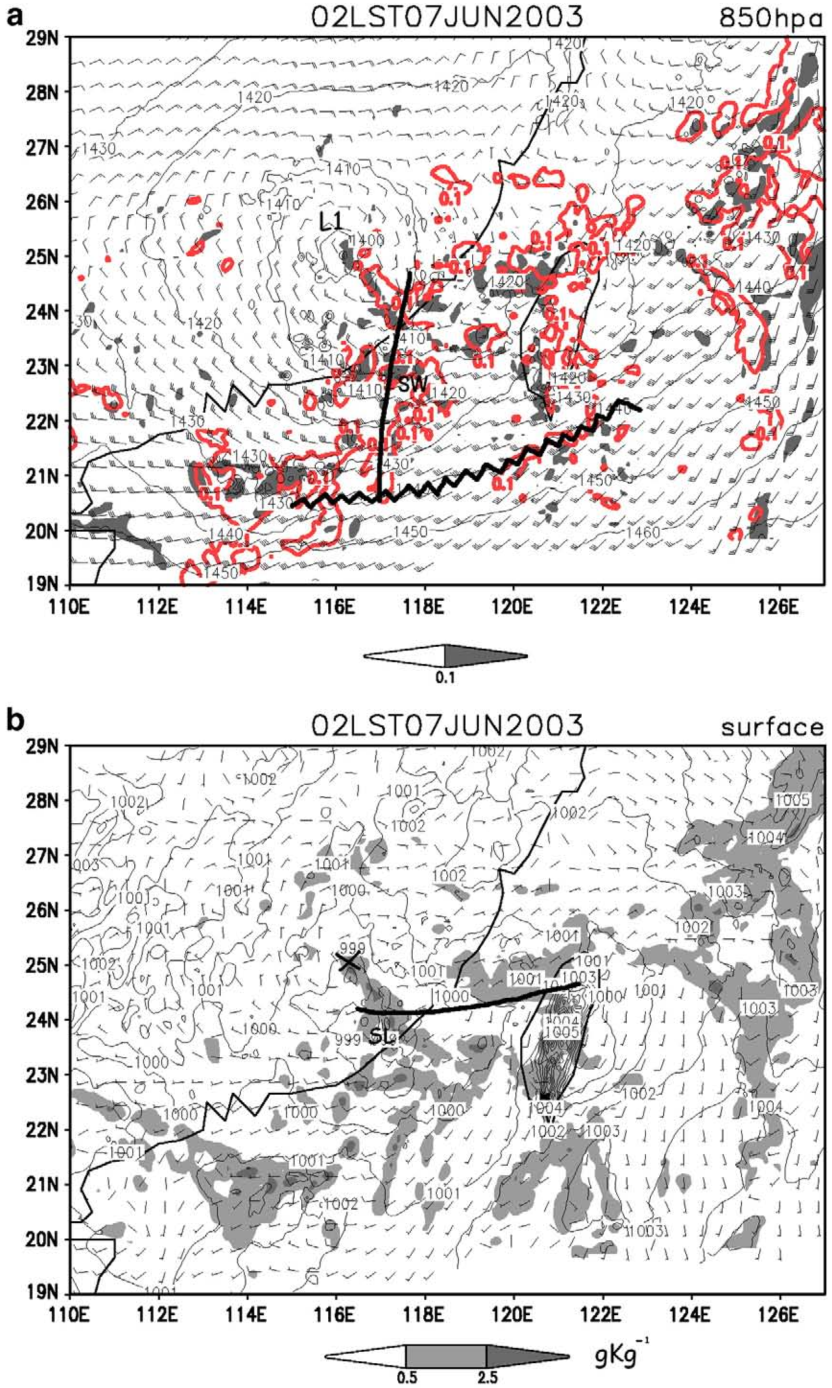

Fig. 7. (a) The simulated 850 hPa heights (solid lines, 10 gpm contour interval) and winds at 0200 LST 7 June in the 12 km grid spacing simulation. The areas enclosed by red lines denote 500 hPa upward motion exceeding 0.1 m s^{-1}. The heavy solid line denotes the 500 hPa shortwave trough SW. The shaded areas represent 850 hPa upward motion exceeding 0.1 m s^{-1}. L1 denotes a low-pressure center. The zigzag line represents 850 hPa LLJ axis with wind speed exceeding 12.5 m s^{-1}. (b) The simulated surface pressure (solid line, 1 hPa contour interval), winds, and cloud water in the 12 km grid spacing simulation. The heavy solid line represents the Mei-Yu front. A cross and SL denotes a surface subsynoptic cyclone over southeast China and southeast China coast, respectively. The magnitude of cloud water is shown by the gray scale in g kg^{-1}. (c) Same as (a(b), but for 0800 LST 7 June 2003. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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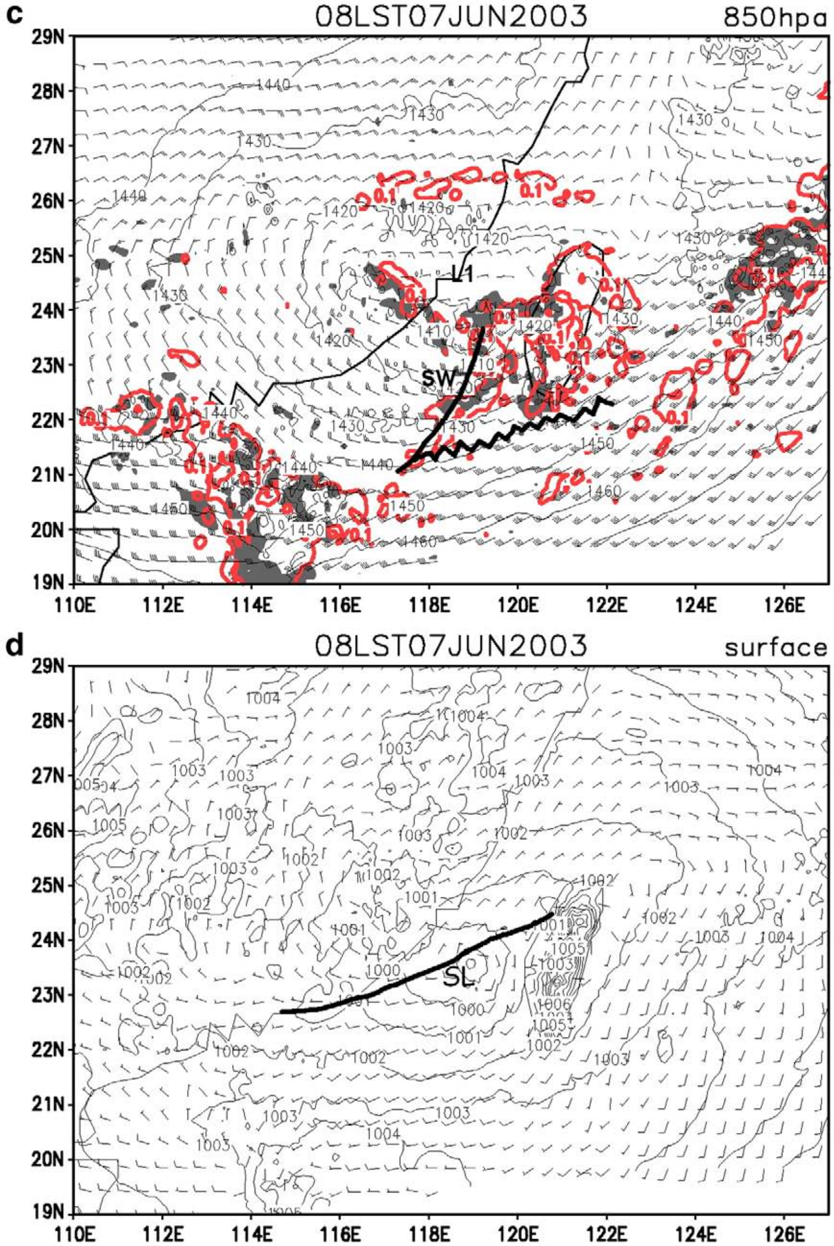
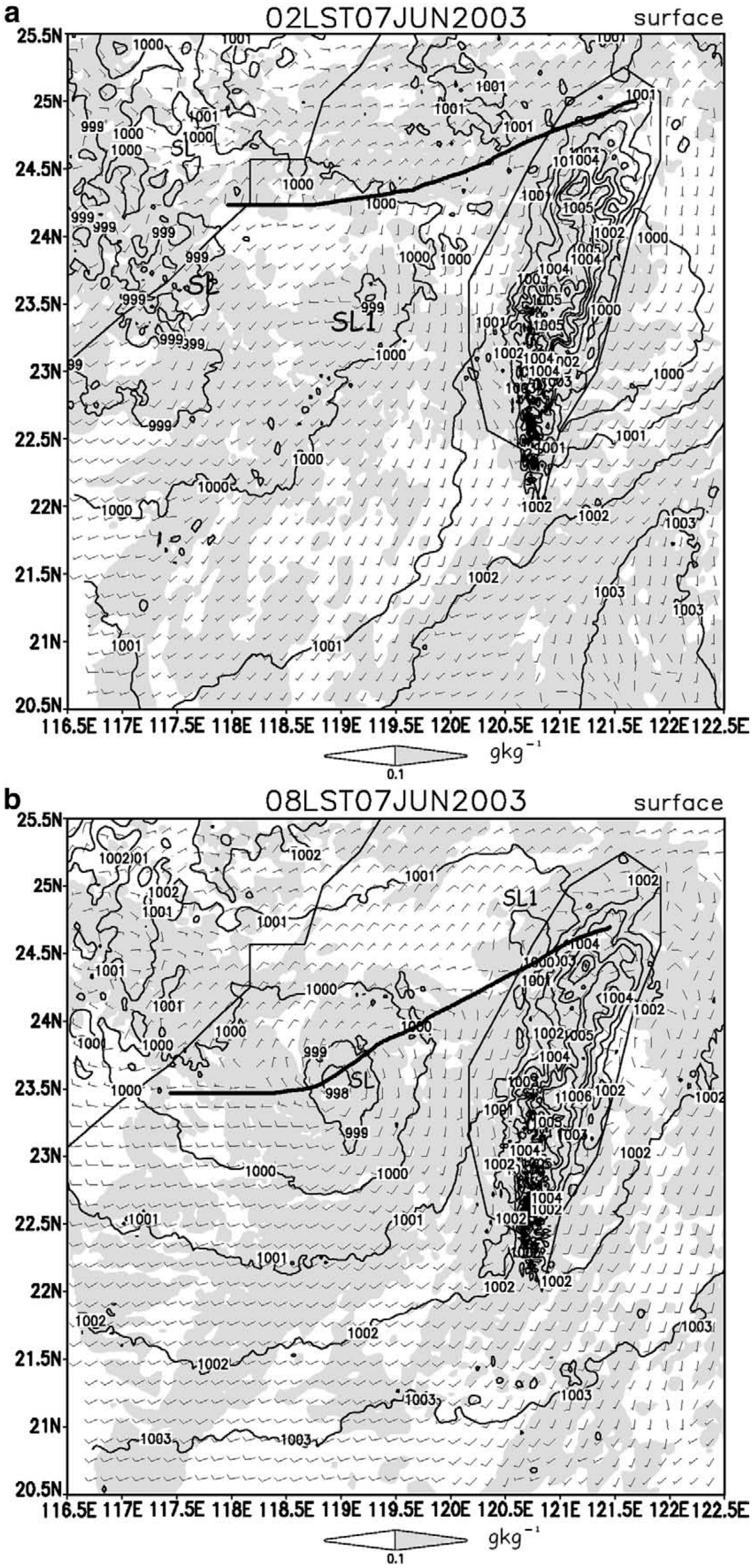


Fig. 7 (*continued*).

coastal areas was enhanced (Fig. 9b). Meanwhile, rainfall continued moving inland and was augmented over the mountains and their slopes (Fig. 9b). The simulated 24 h accumulated rainfall (Fig. 9c) shows that areas over 130 mm of rainfall stretched from the nearby ocean of southwestern Taiwan eastward to the mountains, similar to that observed (Fig. 5d). Very heavy simulated accumulated rainfall over the mountains (Fig. 9c) occurred as was observed (Fig. 5d). The simulation also indicates that there was less accumulated rainfall over the southern part of southwestern Taiwan (near Kuohsiung area) (Fig. 9c) compared to that observed (Fig. 5d). The simulated 24 h accumulated rainfall from the 1.33 km grid spacing simulation shows a higher rainfall accumulation over sloped and mountainous areas of southwestern Taiwan (Fig. 9d) than that in the 4 km grid spacing simulation (Fig. 9c). However the accumulated rainfall in the southern part of southwestern Taiwan (near Kuohsiung area) in the 1.33 km grid spacing simulation (Fig. 9d) is still less than that observed (Fig. 5d).

3.4. Orographic effects on the flow and convection

In order to examine the orographic effects on rainfall, a sensitivity experiment with all of Taiwan's topography



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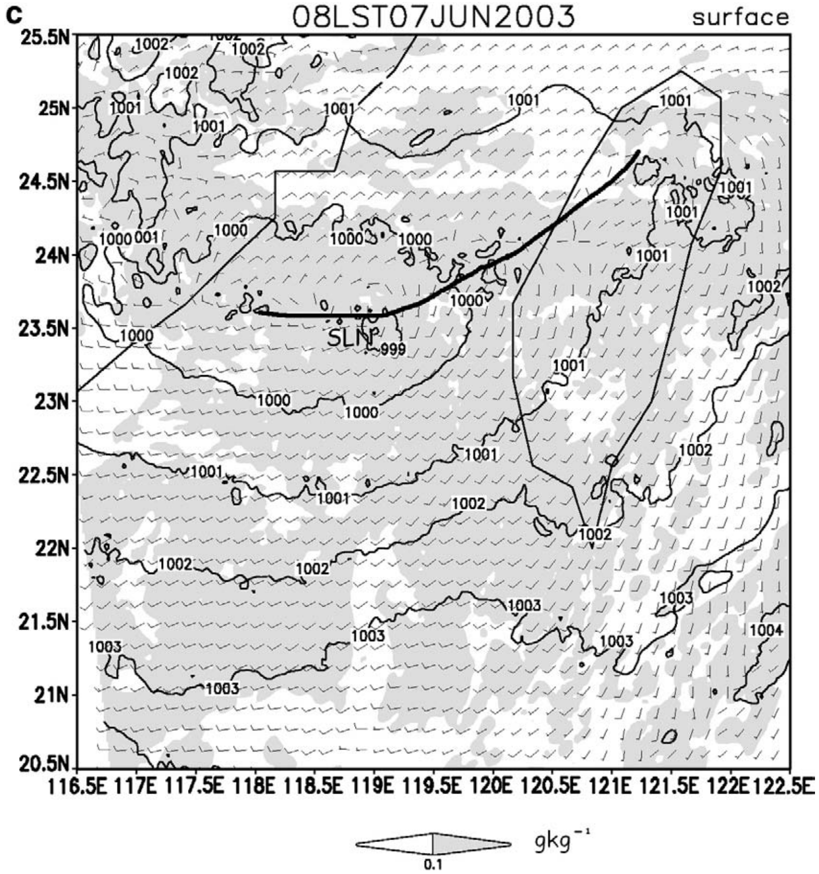

Fig. 8. (a) The simulated surface pressure (solid line, 1 hPa contour interval) and winds in the 4 km grid spacing simulation at 0200 LST 7 June 2003. Heavy solid line represents the approximate location of Mei-Yu front. Areas with cloud water mixing ratio exceeding 0.1 g kg^{-1} are shaded. SL and SL1 represent the subsynoptic cyclones over the northwestern coast of Taiwan and central Taiwan Strait, respectively. (b) Same as (a) however for 0800 LST. (c) Same as (b) however for the NT. SLN represents the subsynoptic cyclone over central Taiwan Strait.

removed (NT) is performed. Similar to the surface SL in the control run (Fig. 8b) at 0800 LST 7 June, the surface subsynoptic cyclone (SLN) in the NT (Fig. 8c) moved from the southeast China coast to the central Taiwan Strait and along the Mei-Yu front (Fig. 8c). Over southwestern Taiwan and its nearby ocean, the southwesterly flow prevailed in the NT (Fig. 8c) instead of the southerly flow in the control run (Fig. 8b). Consequently, the confluence of flow due to flow deflection over southwestern Taiwan resulting from orographic effects found in the control run (Fig. 8b) is absent in the NT. As a result, the surface SLN in the NT over the central Taiwan Strait (Fig. 8c) was slightly weaker than that in the control run (Fig. 8b) because of the lack of extra convergence due to the interaction of the prevailing southwesterly flow and Taiwan topography. Meanwhile, the inland movement of clouds and rainfall over the southern Taiwan Strait toward southwestern Taiwan in the NT did not receive extra lifting over southwestern Taiwan. Consequently, the simulated 24 h accumulated rainfall over southwestern Taiwan in the NT (Fig. 9e) was much less than that in the control runs (Fig. 9c). The simulation results show that the low-level convergence resulted from the confluence of flow due to flow deflection over southern Taiwan and the topographic lifting due to strong wind contribute to high rainfall in 7 June 2003 episode.

4. Summary

The mechanism of the commencement of a heavy rainfall event with accumulated daily rainfall of 379.5 mm over southwestern Taiwan on 7 June 2003 is examined based on the analysis of ECMWF grid data, satellite imagery, radar reflectivity, ARMTS rainfall data, and the WRF model simulations. The analysis of the observed data indicates that an 850 hPa subsynoptic cyclone (containing a low pressure and a vortex) and the surface subsynoptic cyclone were enhanced over the central Taiwan Strait when a 500 hPa hortwave trough approached the Taiwan Strait at 0800 LST 7 June. Concurrently, the 850 hPa low-level jet increased to 21 m s^{-1} over the southern Taiwan Strait. Heavy rainfall commenced over southwestern Taiwan as the region of strong radar reflectivity associated with the surface subsynoptic cyclone moved inland from the southern Taiwan Strait in the warm sector of a Mei-Yu front which extended from northern Taiwan across the surface subsynoptic cyclone to the southeastern China coast. Rainfall over mountainous areas

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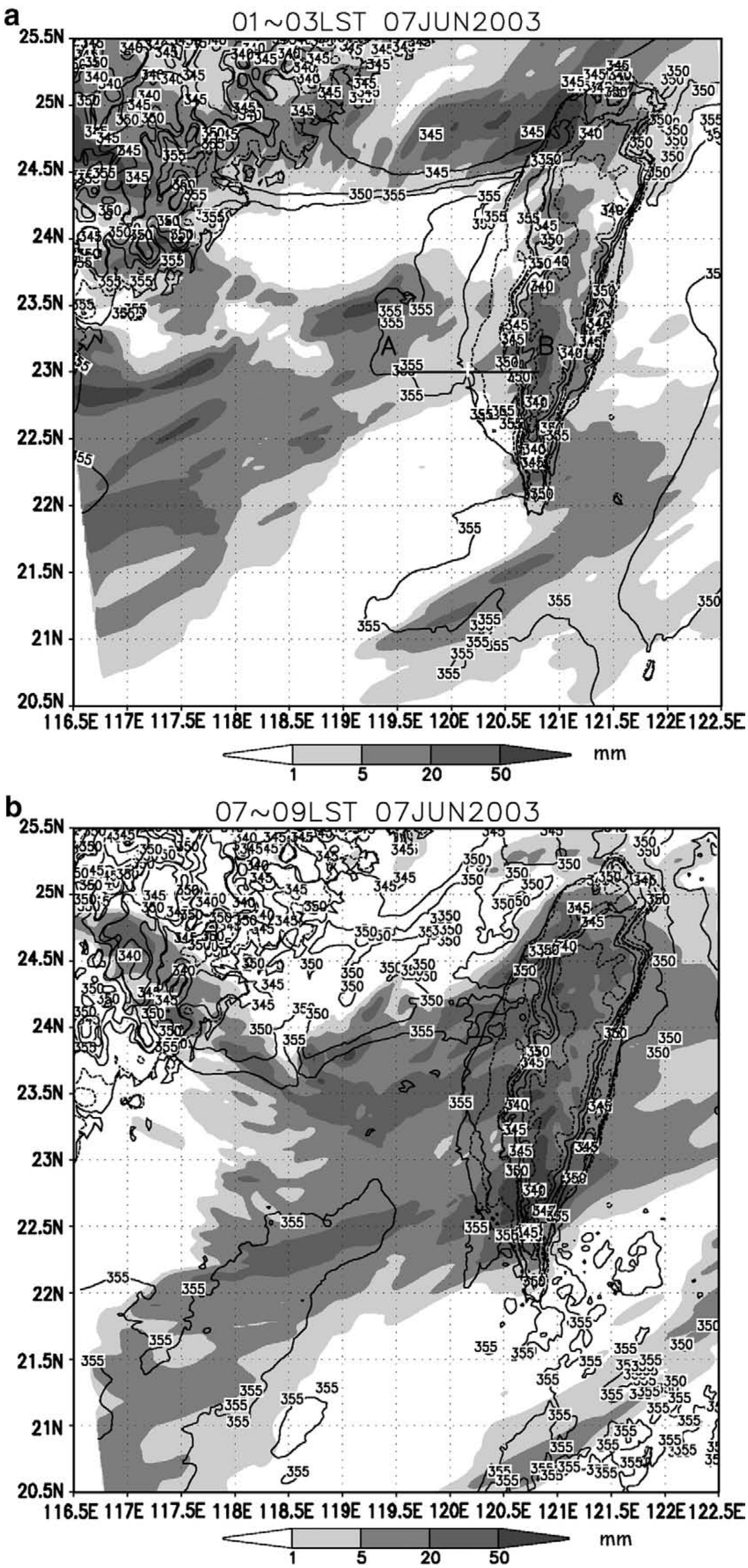

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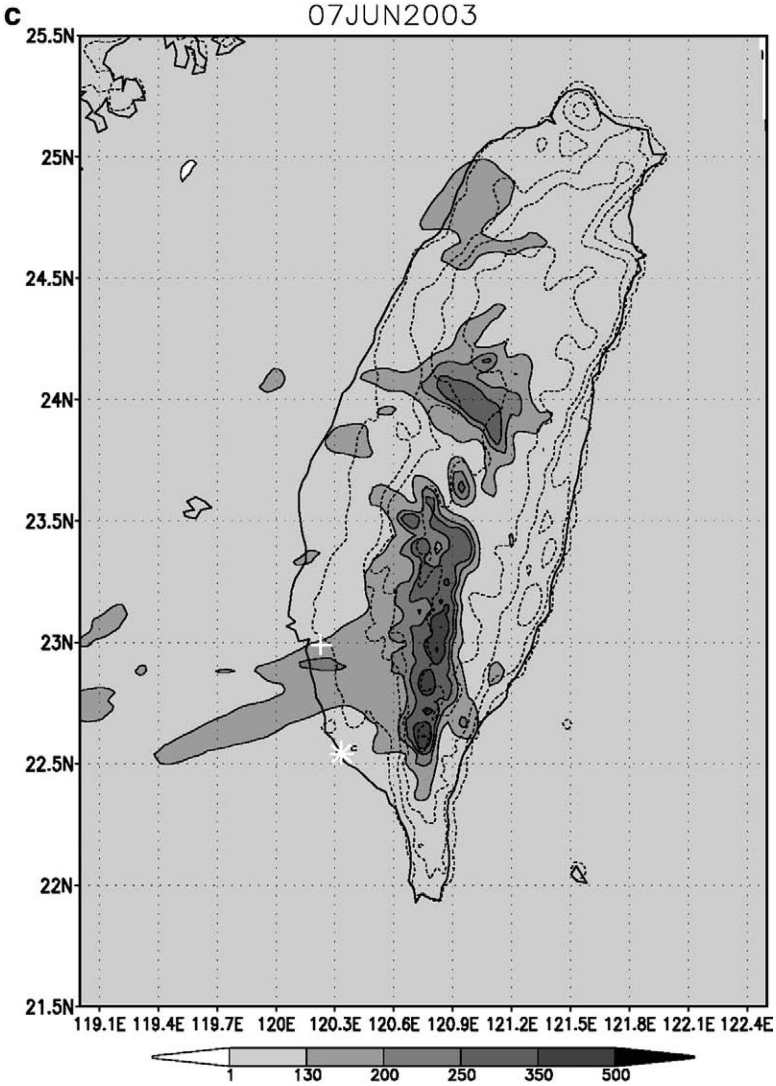

Fig. 9. (a) The simulated accumulated rainfall during 0100–0300 LST June 7 2003 from the 4 km grid spacing simulation. The magnitude of accumulated rainfall is shown by the gray scale in mm. The solid lines represent the equivalent potential temperature of 345, 350, 355 K, respectively. Line AB passing through Tainan (denoted by a cross) is used in Fig. 10. Terrain elevations are shown at 20, 200, 500, 1500, and 2500 m (dotted lines), respectively. (b) Same as (a) however for 0700–0900 LST. (c) The simulated daily accumulated rainfall for 7 June 2003 from 4 km grid spacing simulation. The magnitude of accumulated rainfall is shown by the gray scale in mm. Tainan and Kuohsiung are denoted by a cross and an asterisk, respectively. The terrain elevations are shown at 20, 200, 500, 1500, and 2500 m (dotted lines), respectively. (d) Same as (c) however for 1.33 km grid spacing simulation. (e) Same as (c) however for the NT.

was enhanced by orographic lifting. At the surface, an off-shore flow was observed in the early morning. The interaction of off-shore flow with incoming prevailing flow appeared to enhance rainfall over coastal areas.

The mesoscale processes and orographic effects for producing heavy rainfall are investigated by the WRF model. The simulation results illustrate that an existing 850 hPa subsynoptic cyclone over the eastern slope of the Tibetan Plateau at 0800 LST 5 June moved with a shortwave trough at 500 hPa to southeastern China. Similar to that observed, the simulated 850 hPa subsynoptic cyclone intensified over a wind shear zone over southeastern China as a precursor of 7 June episode. The ascending motion associated with 500 hPa shortwave trough in conjunction with that of the 850 hPa subsynoptic cyclone facilitated a surface subsynoptic cyclone over southeastern China coast at 0200 LST 7 June. At 0800 LST, the intensifying 850 hPa subsynoptic cyclone underneath 500 hPa shortwave trough over the Taiwan Strait strengthened the monsoonal flow or 850 hPa LLJ to 25 m s^{-1} over the southern Taiwan Strait. Heavy rainfall commenced over southwestern Taiwan as the rainfall over the southern Taiwan Strait associated with the surface subsynoptic cyclone moved into southwestern Taiwan and was strengthened there, especially over mountainous areas by the LLJ lifting. In addition, the low-level convergence caused by the deflection of the southwesterly flow near the Taiwan topography and the interaction between an off-shore flow/land-breeze and the prevailing wind also enhanced rainfall over southwestern Taiwan.

In the absence of Taiwan topography (NT), the simulated surface subsynoptic cyclone with 1 hPa weaker than the

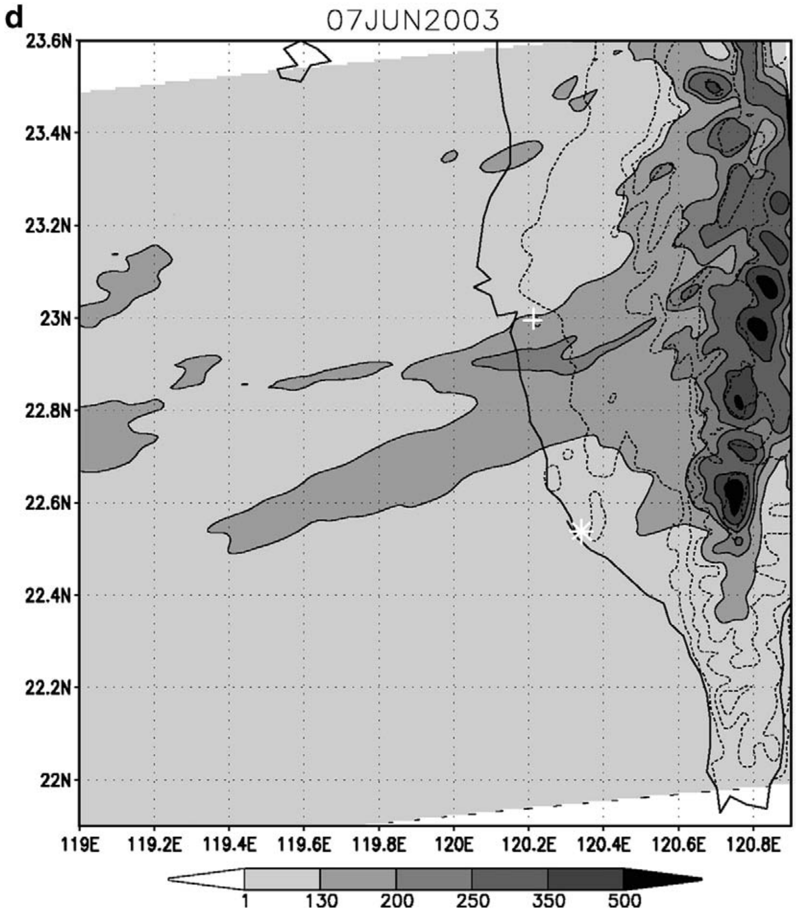

Fig. 9 (*continued*).

control run also appeared in the Taiwan Strait. However, rainfall over southwestern Taiwan was dramatically reduced due to the lack of orographic lifting and the low-level convergence resulted from the confluence of flow due to flow deflection over southern Taiwan. Both the control run and NT revealed that the topographic lifting due to strong wind and low-level convergence caused high rainfall in 7 June 2003 episode.

Acknowledgements

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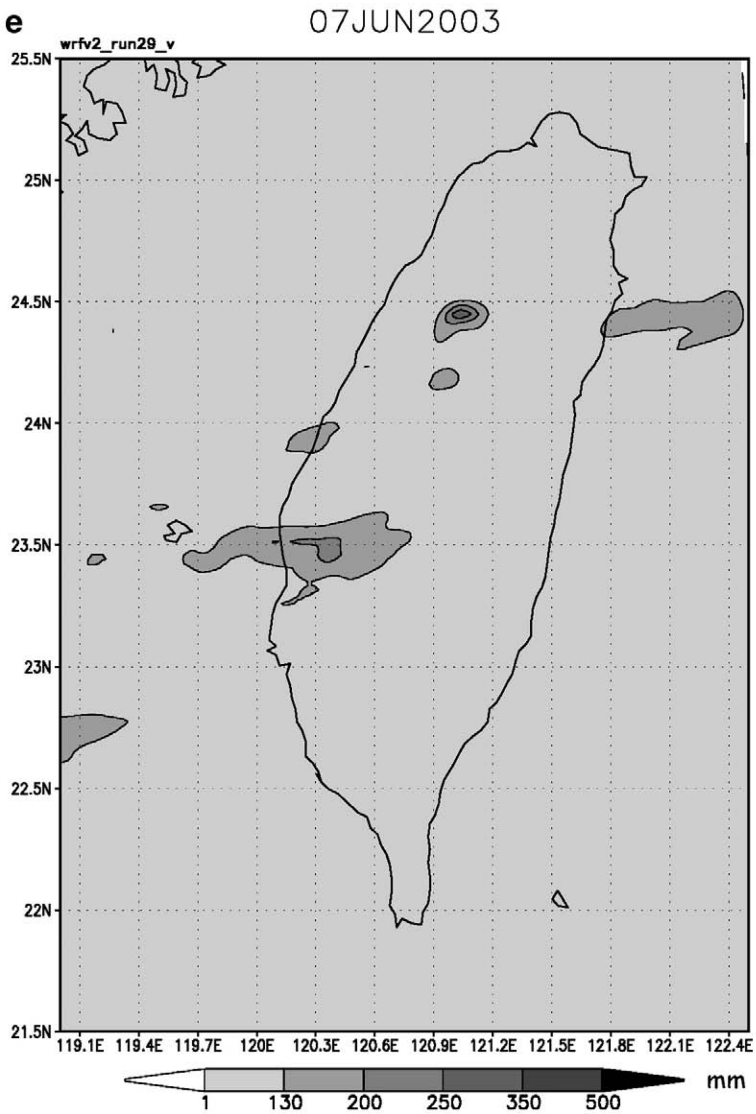

Fig. 9 (*continued*).

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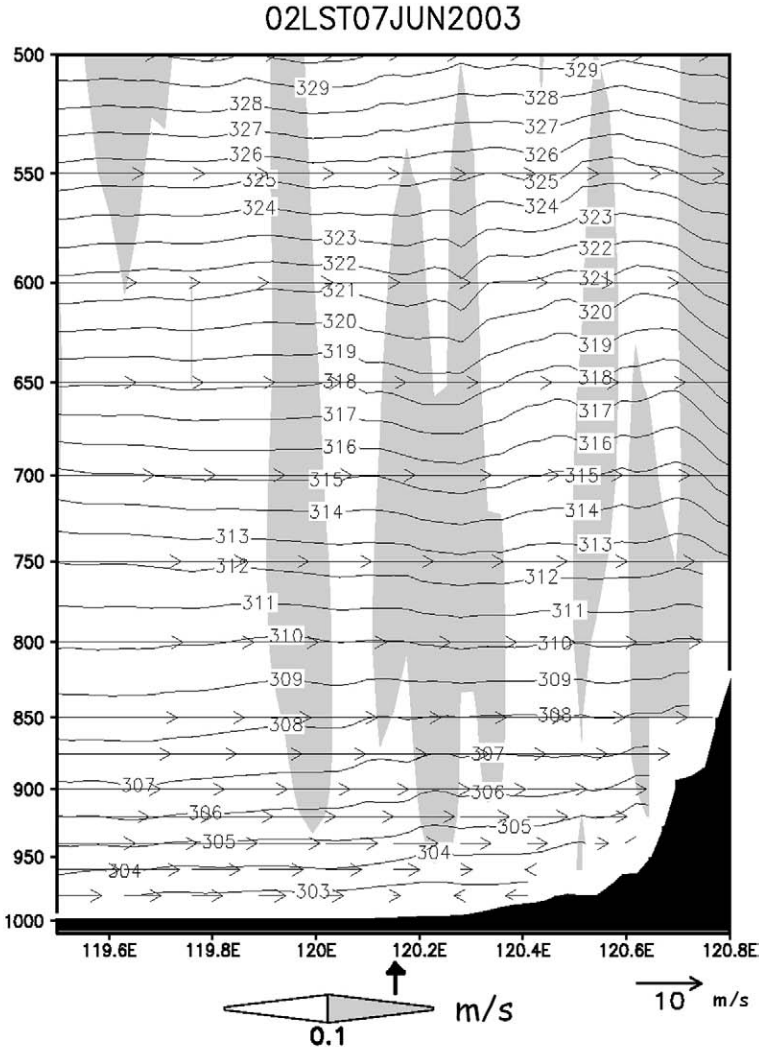

Fig. 10. The east–west wind, upward motion (shaded areas) and virtual potential temperature (solid lines) along a cross section AB passing through Tainan at 0200 LST 7 June 2003 (Fig. 9a). The magnitude of wind (m s^{-1}) is shown by an arrow at the bottom of the figure. The shaded area represents upward motion greater than 0.1 m s^{-1}. The contour interval for virtual potential temperature is 1 K. The terrain is shown at the bottom of the figure. The dark arrow at the bottom of the figure indicates the approximate location of the coastal line.

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