¹ Department of Environmental Management, Tunghan University, Taipei, Taiwan, ROC

² Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan, ROC

³ National Science and Technology Center for Disaster Reduction, Taipei, Taiwan, ROC

Mesoscale simulation and moisture budget analyses of a heavy rain event over southern Taiwan in the Meiyu season

L. T.-C. Chang¹, G. T.-J. Chen², K. K. W. Cheung^{3,*}

With 14 Figures

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Summary

During the period of 29–30 May 2001, the development and northeastward propagation of a series of mesoscale convective systems (MCSs) produced heavy rainfall with a maximum 6-h accumulated rainfall of 120 mm in southern Taiwan. Moisture budget analyses of the MCSs evolution associated with this heavy rain event was carried out by utilizing high-resolution numerical simulation results from the atmospheric part of the triply nested, nonhydrostatic Coupled Ocean/Atmospheric Mesoscale Prediction Systems (COAMPS).

The control (CTRL) run experiment successfully simulated the synoptic environment, although it did not reproduce well the magnitude of the low-level horizontal moisture flux convergence and the precipitation distribution along the Meiyu front over the Taiwan Strait presumably due to insufficient data over the ocean. As QuikSCAT oceanic winds were taken into the assimilation cycles (QUIK run), the experiment reproduced better precipitation in terms of both amount and spatial distribution especially the precipitation over the ocean, and received higher equitable threat score for precipitation forecast. The MCSs evolution was also better simulated as compared to that of the CTRL run.

Moisture budget analyses in the subcloud layer revealed that the grid-scale horizontal moisture flux convergence and up-

ward vertical moisture flux divergence represented the major contribution for moisture transport in all stages of MCS evolution, and their values increased substantially during the convection development. The value of subgrid-scale vertical moisture flux convergence in the 5-km grid (mainly turbulence) was more than double that for convection developed over land than over the ocean. Relative contribution from disturbances under 5 km and cumulus convection were also examined by comparing the subgrid-scale moisture budget terms in the 15-km and 5-km grids, which showed that transport from disturbances under 5 km was dominating for both MCS development over the ocean and land. It was also found that surface evaporation played a relatively important role in the upward moisture transport processes before the development of MCS over the ocean as compared to that during the development of MCS over both land and the ocean. Contribution from orographic effect to rain associated with the MCS and vertical moisture flux convergence in the subcloud layer was discussed based on a flux model of orographic rain.

1. Introduction

Heavy rain events have become major natural disasters around the world. In Taiwan, they often lead to local flooding and debris flows over areas with steep topography that cause severe property damages and loss of lives. In East Asia, the transition period from the northeast monsoon during winter to the southwest monsoon during summer exhibits a distinct seasonal rainfall maximum. The rainfall during this period is called “Meiyu”

* Current affiliation: Kevin K. W. Cheung, Climate Risk Concentration of Research Excellence, Macquarie University, North Ryde, New South Wales, Australia.

Correspondence: George Tai-Jen Chen, Department of Atmospheric Sciences, National Taiwan University, No. 61, Ln 144, Sec. 4, Keelung Road, Taipei, Taiwan 106, ROC (E-mail: george@george2.as.ntu.edu.tw)

in China and Taiwan, and “Baiu” in Japan. There are about four to five frontal systems affecting the Taiwan area during the Meiyu season (mid May to mid June) each year. The Meiyu front is usually accompanied by a nearly continuous cloud band, which produces stratiform and/or convective precipitation (Chen 1992). The heavy rainfall producer in the Meiyu season is the mesoscale convective systems (MCSs) embedded in the Meiyu frontal cloud band (e.g., Chen et al. 1998, 2008; Zhang et al. 2003). Extensive observational data from the Taiwan Area Mesoscale Experiment (TAMEX) (Kuo and Chen 1990) suggested that some mesoscale circulation systems are apparently responsible for the formation of MCSs and heavy rain events. They included the frontal secondary circulation, low-level jet (LLJ), upper-level jet streak, terrain induced flows, outflow boundaries and local circulations (e.g., Johnson and Bresch 1991; Chen 1992; Chen et al. 2000, 2005; Yeh and Chen 2004; Wang et al. 2005).

Efficient moisture transport and accumulation are important factors for MCS development and the subsequent heavy rainfall. Kuo et al. (1986) and Qian et al. (2004) both suggested that the Bay of Bengal is a significant moisture source responsible for the Sichuan flood in 1981 and for heavy rainfall around the Yangtze River area. The MM5 simulation study of Chen et al. (1998) suggested mesoscale LLJ effectively transports moisture to the Meiyu frontal cloud band and helps to maintain convection development. Moisture budget study by Chen (1979) revealed that horizontal moisture flux convergence and vertical flux divergence in the lower troposphere were essential to maintain the Meiyu frontal cloud band. Using dual-Doppler radar datasets collected during the South China Sea Monsoon Experiment (SCSMEX) in 1998, Wang (2004) observed that sufficient moisture transport to convective area and the low-level convergence both play important roles in the convection evolution.

Benjamin and Carlson (1986) found large amount of vertical transport of moisture, heat and momentum fluxes in the lower atmosphere in their numerical simulations, and concluded that the boundary layer was crucial for convective system developed over south central United States. Similarly, the Meiyu frontal structure in the lower atmosphere may also be modified by

the upward transport of surface fluxes that warm and moisten the marine boundary layer (Hong 2002). By using data from European Center for Medium-Range Weather Forecasts/Tropical Ocean-Global Atmosphere (EC/TOGA) and air-sea parameters from Special Sensor Microwave Imager (SSM/I), Liu et al. (2002) observed that the upward transport of surface sensible and latent heat fluxes seem to relate to the development of oceanic MCSs in the vicinity of the Taiwan Strait and the South China Sea during the Meiyu season.

During the period of 29–30 May 2001, a series of MCSs developed along a Meiyu front in the vicinity of Taiwan. One of these MCSs initiated over the Taiwan Strait then moved into Taiwan area. It produced heavy rainfall with a maximum 6-h accumulated rainfall of 120 mm over southern Taiwan. From the synoptic experience, this was a typical case of MCS developed along the Meiyu front. There were two major objectives of this study: (1) to investigate the role of boundary layer processes in moisture accumulation and transportation and (2) to identify the contribution by topography to MCS rain and vertical moisture flux convergence in the boundary layer. Numerical simulations were performed utilizing the atmospheric part of the Naval Research Laboratory's (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997). The COAMPS has a wide range of applications on the research of marine boundary layer dynamics (e.g., Wetzel et al. 2001), orographic flow dynamics (e.g., Doyle et al. 2005), tropical cyclone structure and intensity (e.g., Lin et al. 2002). In this study, moisture budgets were estimated using the COAMPS simulations in the subcloud layer during different stages of the MCS evolution.

2. Case description

The Geostationary Meteorological Satellite (GMS) infrared imageries illustrate that the heavy rain event over southern Taiwan during the period of 29–30 May 2001 was characterized by a series of mesoscale convective systems (MCSs) embedded in a Meiyu front. At 0900 UTC 29 May, a MCS first developed along the southwestern coast of Taiwan (not shown). It was enhanced locally along the coastal area in the following 6 h (Fig. 1a) and produced intense precipitation over

Fig. 1. Irradiance temperature ($^{\circ}\text{C}$) of GMS-5 IR satellite imagery at (a) 1500 UTC 29 May, (b) 1800 UTC 29 May, (c) 2100 UTC 29 May, (d) 0000 UTC 30 May, (e) 0300 UTC 30 May, and (f) 0600 UTC 30 May 2001. Dashed lines depict the surface Meiyu frontal positions, and the [•] in (a) is the location of of Makung rawinsonde station. Dotted lines depict the boundaries of the MCS A

the coastal plain region and some mountainous area. In the meantime, another MCS (hereafter MCS A) started to develop over the southern

Taiwan Strait along the surface Meiyu front by 1800 UTC 29 May (Fig. 1b). MCS A slowly propagated toward Taiwan in the subsequent

Fig. 2. Accumulated precipitation (mm) observed over Taiwan in the period of 0000–0600 UTC 30 May 2001. Contour levels of 20, 40, 80 and 120 mm. The terrain over 2500 m is shaded which indicates the Central Mountain Range (CMR)

hours (Fig. 1c) and the center of intense convection moved into southern Taiwan area by 0000 UTC 30 May (Fig. 1d). During the subsequent few hours, MCS A was likely enhanced locally by the topography (Fig. 1e–f) that will be discussed further in Sect. 4. The boundary of MCS A as delineated by irradiance temperature of GMS at -52°C was illustrated by dotted lines in Fig. 1. The surface Meiyu frontal position over the ocean in Fig. 1 was defined by surface synoptic analysis adjusted by wind shift line revealed in 50-km resolution QuikSCAT oceanic winds (Graf et al. 1998). The wind shift line was defined as the boundary between southerly wind component and non-southerly wind component similar to that used by Yeh et al. (2002).

The 6-h accumulated precipitation from 0000 to 0600 UTC 30 May indicates that the area of rainfall associated with MCS A spread inland (Fig. 2). The maximum rainfall occurred at the southern tip of the Central Mountain Range (CMR, area $\geq 2500\text{ m}$ shaded) and the 6-h accumulated precipitation reached 120 mm. The Tropical Rainfall Measuring Mission (TRMM) rainfall rate estimations using the 3B42 calibration algorithm (e.g., Kummerow et al. 2000) at 0000 UTC 30 May 2001 indicated that a maximum precipitation center was over the ocean to the southwest of Taiwan in association with MCS A (Fig. 3).

Fig. 3. TRMM estimated rainfall rate valid at 0000 UTC 30 May 2001 (shading, in mm h^{-1}). Dashed lines depict the observed surface Meiyu frontal positions

Fig. 4. (a) Surface, (b) 925-, (c) 850-, and (d) 500-hPa NOGAPS analyses at 1200 UTC 29 May 2001. Solid lines are contours for (a) surface pressure (hPa) and (b)–(d) height fields (m). Thin dashed lines are contours for (a) temperature (K), (b)–(c) equivalent potential temperature (K) and (d) absolute vorticity (10^{-6} s^{-1}). The heavy dashed lines in (a)–(c) depict Meiyu frontal position. Full and half barbs represent 5 and 2.5 m s^{-1} , respectively and areas with wind speed $\geq 12 \text{ m s}^{-1}$ in (b)–(c) are shaded

The Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Brody 1993) analyses with 1° lat./lon. resolution at 1200 UTC 29 May 2001 indicate that a Meiyu front in the vicinity of Taiwan was oriented in a northeast to southwest direction (Fig. 4a–c). Note that the Meiyu front was located at the southeastern boundary of the area with intense equivalent potential temperature gradient. It possessed relatively strong baroclinity with shallow

and northwest-slanting frontal structure similar to that observed during the TAMEX (e.g., Chen 1992). Prefrontal southwesterlies in lower troposphere extended over a large area from the South China Sea to areas east of Taiwan with a speed over 12 m s^{-1} , which satisfied the definition of LLJ in the Meiyu season (Chen and Yu 1988) (Fig. 4b and c). Southwesterlies also prevailed over the same area in mid-troposphere with slightly weaker intensity (Fig. 4d).

Fig. 5. Surface horizontal moisture flux convergence ($10^{-8} \text{ kg m}^{-3} \text{ s}^{-1}$) derived from NOGAPS analyses at (a) 1200 UTC 29 May and (b) 0000 UTC 30 May 2001. The thick dashed lines depict Meiyu frontal positions

Figure 5 reveals that the NOGAPS-derived surface horizontal moisture flux convergence covered a large area extending from the South China Sea to the Taiwan Strait. The QuikSCAT oceanic winds at the same time also indicate strong wind convergence over Taiwan Strait (not shown) which may lead to the horizontal moisture flux convergence. However, the strong flux convergence derived from NOGAPS was more to the

south as compared to the IR satellite imagery analysis shown in Fig. 1b–d. Since strong moisture flux convergence is important to convection initiation (Banacos and Schultz 2005), this suggests that the NOGAPS analyses cannot resolve moisture and wind fields of the synoptic environment associated with MCS A development satisfactorily. The magnitude of horizontal moisture flux convergence decreased from surface to 925-hPa (not shown) over the areas where the MCSs developed, thus the moisture essential for MCS A development mostly originated from the boundary layer.

There is a station Pingtung at southwestern Taiwan that releases sounding and its location is ahead of the front. However, sounding data from this station was missing during the two-day period in this case. Therefore, the environmental condition six hours before the initiation of MCS A over the Taiwan Strait is examined using a sounding launched at the Makung station (23.7° N , 119.6° E) at 1200 UTC 29 May (Fig. 6). Sounding at Makung station indicates that dew point depression was small in the lower- and mid-troposphere, and the temperature lapse rate was greater than moist- and smaller than dry-adiabatic lapse rate. Therefore, the atmosphere was conditionally unstable and moist in the lower to middle troposphere. Weak and shallow northeasterlies ($\sim 2.5 \text{ m s}^{-1}$) with temperature 25.8° C at 1000 hPa indicated that Makung was located in postfrontal air mass, a fact that is also consistent with the frontal position analyzed in Fig. 4a. However, relatively strong southwesterlies ($\sim 5 \text{ m s}^{-1}$) in the lower troposphere indicates the prefrontal environment. The convective available potential energy (CAPE) for an air parcel released from 1000-hPa (within postfrontal cold air) was computed using this sounding and a value of $1307.3 \text{ m}^2 \text{ s}^{-2}$ was obtained. The value is quite similar to the estimated CAPE of $1330 \text{ m}^2 \text{ s}^{-2}$ for the composite squall line during mature stage observed in TAMEX (Chen and Chou 1993). Thus, the sounding vertically penetrated through the Meiyu front, and was representative of the environment in which MCS A developed. Comparison with other surface stations on Taiwan Main Island indicated that the temperature dropped only 0.4° C across the front and the low-level environment was very moist. Therefore, deep convection could develop easily

Fig. 6. Skew- T -log- p diagram for the sounding taken at Makung station 46734; near 23.7° N, 119.6° E; the [●] in Fig. 1a at 1200 UTC 29 May 2001. The convective available potential energy (CAPE) for an air parcel released at the surface is $1307.3 \text{ m}^2 \text{ s}^{-2}$

in this environment if lifting mechanism existed in the lower atmosphere. Furthermore, the convective Richardson number was estimated to be around 160, favorable for ordinary convective cells to occur (Weisman and Klemp 1982).

3. Model description and design of experiment

The atmospheric part of COAMPS was utilized in this study. COAMPS is a nested, three-dimensional model that solves the non-hydrostatic, fully compressible equations of motion on a terrain-following sigma coordinate system (Gal-Chen and Somerville 1975). The simulation had three nested domains defined by a grid of 61×61 points for the coarse mesh, 100×82 points for the medium mesh and 112×112 points for the fine mesh. The horizontal grid increment was 45, 15 and 5 km for the coarse-, medium- and fine-mesh grids, respectively (Fig. 7). There were 30 irregularly spaced levels in the vertical, 11 levels

Fig. 7. Domain configuration for COAMPS model simulations used in this study. Three nested domains with grid increments of 45, 15, and 5 km, respectively were adopted

of which were below 1.6 km for sufficiently resolving boundary layer processes. Furthermore, a 1-km resolution terrain and landuse dataset was utilized to setup the domains used in the simulations (not shown). The Kain and Fritsch (1993) cumulus parameterization scheme was used to parameterize the subgrid-scale moist convective process in the coarse and medium grids, whereas the moist processes in the fine grid were explicitly predicted from microphysical budget equations following Rutledge and Hobbs (1983). Long-wave and shortwave radiation processes were parameterized following Harshvardhan et al. (1987). As for planetary boundary layer parameterization, COAMPS utilizes a level-2.5 scheme (Mellor and Yamada 1982) that solves both prognostic equation for turbulent kinematic energy (TKE) and diagnostic equations for second-moment quantities such as fluxes of heat, moisture and momentum. Schemes with this feature are re-

ferred to as 1.5-order closure schemes. The approach in Louis (1979) was used to compute surface fluxes.

The control run (CTRL) experiment consisted of a 54-h simulation starting at 1200 UTC 28 May 2001 with four incrementally updated assimilation cycles of 12-h periods (Fig. 8), similar to that in Lin et al. (2002) and Burk and Thompson (2004). The first cycle began with a cold-start 18-h simulation that was initialized directly from the NOGAPS analyses with 1° lat./lon. resolution. The following three warm-start 18-h simulations were restarted from a previous 12-h forecast. In each cycle, data in the 6–18-h period was used for analysis to avoid data adjustment problem in the first 6 h. In this way, simulated data throughout the 48-h period from 1800 UTC 28 May to 1800 UTC 30 May is available for later diagnosis. In every assimilation cycle, the model's first guess field was updated with

Fig. 8. Initialization and data assimilation cycling of COAMPS (CTRL run). The thick solid arrow represents a timeline of the simulation, with the first two digits indicating the date and the last two the hour. The observed heavy rain event occurred in the period of 27–45 h model forecast as indicated by double dash lines at the bottom of the diagram. Shaded periods are used for diagnosis

observations using the multivariate optimum interpolation (MVOI) scheme. Throughout the 54-h simulation, NOGAPS forecast fields were adopted as the lateral boundary conditions.

As will be discussed in Sect. 4, the CTRL run experiment successfully simulated the synoptic environment. However, it did not reproduce well the magnitude of the low-level horizontal moisture flux convergence along the Meiyu front over the Taiwan Strait and the precipitation distribution over Taiwan area. In order to improve the simulation, the QuikSCAT oceanic winds were blended into the COAMPS analysis in the simulation called the QUIK run. The QUIK run was conducted with full physics and the same model configuration as that in CTRL run except that QuikSCAT oceanic winds with 50-km resolution were blended into the initial conditions of every 12-h assimilation cycle using the MVOI scheme. In both experiments, the heavy rain event over southern Taiwan occurred approximately in the period of 27–45 h after the model initialization time.

4. Model validation

The TRMM rainfall rate estimations at 0000 UTC 30 May 2001 indicated maximum precipitation centers over the ocean both to the northeast and southwest of Taiwan (Fig. 3). The simulated precipitation in the coarse grid of the CTRL run valid at the same time had a smaller amount of precipitation over these regions (Fig. 9a). On the other hand, the QUIK run generated better precipitation at this time in terms of both the amount and the spatial distribution especially the precipitation associated with MCS A over the southern Taiwan Strait (Fig. 9b). Note that the rain rate at the CMR was over predicted in both runs but focus was put on system development over the ocean. Furthermore, the surface Meiyu frontal position, especially the branch west of Taiwan, defined by the simulated 10-m wind shift line in the QUIK run (dashed line in Fig. 9b) was north of that in the CTRL run, and agreed better with that defined by QuikSCAT oceanic winds in Fig. 3.

The overall distribution and magnitude of simulated surface horizontal moisture flux convergence were well represented by the QUIK run at 1200 UTC 29 May (Fig. 10a). The coarse-grid QUIK run also resolved more mesoscale details than those derived from NOGAPS analyses

Fig. 9a. Simulated precipitation from the coarse grid in CTRL run (contour levels of 1, 2, 4 and 6 mm h⁻¹) valid at 0000 UTC 30 May 2001, and (b) as in (a), except for QUIK Run. Dashed lines depict simulated surface Meiyu frontal positions

(Fig. 5a). On the other hand, the corresponding horizontal moisture flux convergence in the CTRL run had its area of maximum in the Taiwan Strait south of that in the NOGAPS analyses (not shown). The simulated surface horizontal moisture flux convergence in the QUIK run valid at 0000 UTC 30 May showed that area of maximum value over the Taiwan Strait (Fig. 10b) agreed well with location of MCS A (Fig. 1d). This suggests that the evolution of low-level winds and moisture content was well captured in the QUIK run simulation.

Fig. 10. Simulated surface horizontal moisture flux convergence ($10^{-8} \text{ kg m}^{-3} \text{ s}^{-1}$) for 45-km-resolution grid in QUIK run valid at (a) 1200 UTC 29 May and (b) 0000 UTC 30 May 2001. The thick dashed lines indicate Meiyu frontal positions

Simulated 1-h accumulated precipitation in the 5-km grids from both runs were further examined to serve as a proxy for MCSs evolution. Figure 11 presents the simulations for 5-km grid QUIK run. Rain areas with a certain threshold not necessarily

resembles regions in satellite imageries with cold cloud-top temperatures because irradiance temperatures in satellite imageries only reveal cloud-top situations and that rain field moves with propagation of the system, so the area with simulated 1-h accumulated rain over 0.1 mm h^{-1} only matched roughly with the boundary of MCS A defined in Fig. 1. At 1500 UTC 29 May while a MCS developed over southwestern Taiwan (Fig. 1a), an area of intense precipitation was resolved (Fig. 11a) and located roughly over the same area. The 1-h accumulated precipitation valid at 1800 UTC 29 May (Fig. 11b) further indicated another area of simulated precipitation maximum over southern Taiwan Strait was closely related to the MCS A development (Fig. 1b). The simulated 10-m wind field indicated that horizontal convergence (not shown) was associated with the surface Meiyu front, which may be crucial for the large horizontal moisture flux convergence to occur for the subsequent development of MCS A over the same area. Furthermore, the 1-h accumulated precipitation valid at 2100 UTC 29 May, 0000 and 0300 UTC 30 May also indicated that the propagation of rain associated with MCS A extended into southwestern Taiwan when the MCS moved over land (Fig. 11c–e). The maximum rainfall center propagated northeastward along the front toward Taiwan although the simulated position was a bit north of the observed position of MCS A in satellite imageries (Fig. 1c–e). The simulated rain further extended into central Taiwan at 0600 UTC 30 May (Fig. 11f) and had a maximum up to 15 mm h^{-1} over the western slope of CMR. On the other hand, the 5-km grid CTRL run only generated a MCS with slower development and less amount of precipitation in the region (not shown). Note that the comparison here serves only for a first order model validation and later analyses of moisture budget (Sect. 5) will follow exactly the simulated rain field instead of the rough MCS boundary estimation from satellite imageries.

A flux model of orographic rain in Lin et al. (2002) was utilized to estimate the influence from

Fig. 11. Simulated 1-h accumulated precipitation (contour levels of 0.1, 5, 15 and 30 mm) and 10-m wind vector (ms^{-1}) for the 5-km-resolution grid in QUIK run valid at (a) 1500 UTC 29 May, (b) 1800 UTC 29 May, (c) 2100 UTC 29 May, (d) 0000 UTC 30 May, (e) 0300 UTC 30 May and (f) 0600 UTC 30 May 2001. Dashed lines depict the simulated surface Meiyu frontal positions. The terrain over 2500 m is shaded

terrain on precipitation of MCS A. Orographic rain was defined as

$$P_{\text{orography}} = \frac{\rho}{\rho_w} E(V_H \cdot \nabla h) \frac{qL_s}{c_s}, \quad (1)$$

where ρ is air density, ρ_w the liquid water density, E the precipitation efficiency (assumed to be one here), h the terrain height, q the mixing ratio, L_s the horizontal scale of the convective system, c_s the propagation speed of the convective system (and hence L_s/c_s is the time scale of interest that

is 1 h here), and the horizontal wind field V_H at 850-hPa was used. At 0000 UTC 30 May most of the rain associated with MCS A was over the ocean (Fig. 11d) and the Eq. (1) indicated that contribution from orography was minimal. Three hours later the raining area moved inland and the orographic rain model indicated that up to about 15 mm h^{-1} of rain at the western side of CMR potentially attributed to orography (Fig. 12a). Therefore, it can be said that the Meiyu mode of MCS precipitation continued until about 0300 UTC 30 May and the orographic mode commenced. This orographic influence persisted in the next few hours at southern Taiwan (Fig. 12b) and the maximum rain rate is also about 15 mm h^{-1} that is almost identical to the simulated rain in the same area in Fig. 11f. That is, in the orographic mode it is likely that the simulated rain at the southern end of Taiwan was entirely due to orographic lifting. The rain maxima to the north in Fig. 11e and f was associated with the MCS development itself and less affected by orography. Although results from this flux model were sensitive to the level of wind field and topography data (about 1-km resolution in COAMPS) used, additional calculations were performed on several other levels such as 925 hPa and similar results were obtained, indicating robustness of this rainfall mode separation.

In order to quantify the precipitation forecast skill in both the CTRL and QUIK runs, the corresponding equitable threat score (ETS, Schaefer 1990) was computed. The definition of ETS is the same as the standard threat score except that the numerator (H) and the denominator ($F + O - H$) are both subtracted by the expected number of hits in a random forecast R :

$$\text{ETS} = \frac{H - R}{F + O - H - R}, \quad (2)$$

where H is the number of hits when both observed and forecast rainfall amounts are greater than the specified threshold. F and O are the respective numbers of forecast and observed samples when the rainfall amount is greater than the threshold. The quantity R , which is equal to FO/N , is the random forecast in which N is the total number of points being verified. For verification, 344 rain gauge stations irregularly distributed over Taiwan were interpolated to the 5-km model grid (Cressman 1959). The 12-h accumu-

Fig. 12. Orographically induced 1-h precipitation (contour levels of 0.1, 5, 10, 15 and 20 mm) based on simulated results of 5-km resolution grid in QUIK run valid at (a) 0300 UTC and (b) 0600 UTC 30 May 2001. Terrain height over 2500 m is shaded

lated rainfall amount was then compared with the model-simulated precipitation amount with a threshold of 2.5 mm. During the periods of model integration for 0–12 h, 12–24 h, 24–36 h and 36–48 h, the ETS's in the CTRL run were 0.06, 0.18, 0.19 and 0.18, respectively. The corresponding ETS's for the QUIK run were 0.07, 0.17, 0.24 and 0.22. Both experiments clearly had better precipitation forecast after the first assimilation cycle (0–12 h), and comparatively the QUIK run performed relatively better than the CTRL run after the end of the second assimilation cycle. Moreover, the ETS's in the two experiments for the 24–36-h period (valid at 2000 LST 29 – 0800 LST 30 May) were both higher than those for the 36–48-h period (valid at 0800 LST – 2000 LST 30 May), which indicates that nighttime precipitation was more accurately predicted in our model than daytime precipitation. This was primarily due to the underestimation of daytime radiative heating and hence convective activity, similar to that found in the MM5 simulations of Chien et al. (2002).

Dynamic and thermodynamic parameters associated with MCS A computed in the fine domain including the wind field, vorticity, temperature, and cloud liquid water content were also examined. The maximum 850-hPa relative vorticity associated with MCS A was $1.5 \times 10^{-4} \text{ s}^{-1}$ at 2100 UTC 29 May, and these vorticity centers collocated with the observed maximum precipitation centers. The vertical distribution of cloud liquid water mixing ratio with value larger than zero g kg^{-1} indicated that the convection associated with MCS A was up to about 10 km. Moreover, the maximum vertical velocity about 55 cm s^{-1} in area of MCS A occurred at a level around 7 km. Although there was no available radar reflectivity data during the periods of MCS A development for verification purpose, all these features of the simulated MCS A are similar to the MCSs observed in North America (e.g., Schumacher and Johnson 2005) and also those for simulated MCS in the Meiyu season (Zhang et al. 2003).

5. Diagnosis of moisture budget

5.1 Methodology

As discussed in the previous section that by blending QuikSCAT oceanic winds into model

assimilation cycles, the predicted rainfall distribution associated with the MCS A evolution was improved. Thus, moisture budget analyses were carried out using 5-km resolution simulation results from the QUIK run to reveal the moisture transport processes associated with the MCS A development.

The continuity equation for water vapor in height coordinate with the molecular diffusion term neglected can be written as,

$$\frac{\partial q}{\partial t} + \nabla \cdot (V_H q) + \frac{\partial(wq)}{\partial z} = \frac{S}{\rho}, \quad (3)$$

where q is mixing ratio of water vapor, V_H horizontal wind vector, w vertical velocity in height coordinate, ρ air density, and S sources and sinks of water vapor. With the incompressible assumption, if variables in (3) are partitioned into mean (bar) and perturbation (prime) part and the equation is averaged by applying Reynold's averaging rules, one has

$$\frac{\partial \bar{q}}{\partial t} = \underbrace{-\nabla \cdot (\bar{V}_H \bar{q})}_{\text{HF}} - \underbrace{\frac{\partial(\bar{w}\bar{q})}{\partial z}}_{\text{VF}} - \underbrace{\nabla \cdot (\bar{V}'_H \bar{q}')}_{\text{SHF}} - \underbrace{\frac{\partial(\bar{w}'\bar{q}')}{\partial z}}_{\text{SVF}} + \underbrace{\frac{\bar{S}}{\rho}}_{\text{EC}}. \quad (4)$$

The mean quantities LC, HF and VF were calculated from the simulation results in the inner mesh domains of the QUIK run. Thus, term LC represents the local rate of change of resolvable grid-scale water vapor, while terms HF and VF denote resolvable grid-scale horizontal and vertical moisture flux convergence, respectively. On the right-hand side of (4), the sets of prime terms SHF and SVF represent the subgrid-scale horizontal and vertical moisture flux convergence that describe how moisture is transported by subgrid-scale processes. Since COAMPS solved explicit moisture equation in 5-km resolution domain without cumulus parameterization, this resolution presumably was able to resolve most of ordinary convective cells in MCS A. Thus, although there may be sub-5-km updrafts and downdrafts near the cloud base associated with convection not resolved by the 5-km grid, it was assumed that subgrid-scale processes in the planetary boundary layer for the 5-km run consisted mainly of turbulent transport. On the other hand, subgrid-scale processes in the 15-km resolution simulation included both turbulent and cumulus convective transport, and comparison between

the moisture budget from these two grids with different resolution in Sect. 5.3 was used to roughly distinguish turbulent and cumulus transport.

Subgrid-scale terms in the planetary boundary layer were computed based on formulation of turbulent transport in COAMPS, which was parameterized by K -theory with a predicted TKE budget based on a level-2.5 scheme of Mellor and Yamada (1982). Therefore, the turbulent second moment quantities (i.e., the terms $\overline{V_H'q'}$ in SHF and $\overline{w'q'}$ in SVF of Eq. (4)) were parameterized in terms of mean quantity of each grid point. Whereas early K -theory models prescribed a constant eddy coefficient K value, in COAMPS the K formulation is given by a polynomial function of R_{if} (flux Richardson number) multiplied by the turbulent length scale and $(TKE)^{1/2}$, and is updated in every time step. Noted that SVF at the first level of the model (10-m) was derived from the difference between the turbulent moisture flux ($\overline{w'q'}$) term in the simulated surface latent heat flux and that for the second model level at 30 m. The last term EC represents evaporation and condensation. It was computed as a residual term to balance the other terms in (4). A simple centered finite-difference scheme was used to compute all spatial and time derivatives. The units for all term are mass of water vapor per volume per unit time ($\text{kg m}^{-3} \text{s}^{-1}$).

As mentioned in Sect. 2, MCS A initiated over the Taiwan Strait at 1800 UTC 29 May, the center of intense convection then moved into Taiwan area by 0000 UTC 30 May and dissipated after 0600 UTC 30 May. Since we are interested in the moisture transport processes associated with evolution of MCS A, hourly model output at each 5-km resolution grid point was then used to calculate moisture budget. The threshold of 0.1 mm h^{-1} simulated rainfall rate was chosen to delineate the areas of MCS A during the period of 1800 UTC 29 May to 0600 UTC 30 May. Data at grid points with simulated rainfall rate over 0.1 mm h^{-1} were averaged to investigate the moisture transport processes during the convection development. The area averaging of moisture budget was also performed 3 h before MCS A initiation (1500–1800 UTC 29 May) and 3 h after MCS A dissipation (0600–0900 UTC 30 May). The areas of MCS development in these

two periods were simply extrapolated backward and forward from that at 1800 UTC 29 May and 0600 UTC 30 May, respectively.

5.2 Budget analyses

To investigate the processes involved in moisture variations, area averaged moisture budget values in height-time cross sections are presented in Fig. 13. Moisture transport by resolvable grid-scale processes (i.e., horizontal and vertical moisture flux convergence, HF and VF), local rate of change of water vapor (LC) and the vertical velocity (w) are given in Fig. 13a–d, respectively. The moisture transported by subgrid-scale processes (i.e., subgrid-scale vertical moisture flux convergence, SVF) in the boundary layer is also presented (Fig. 13e). The lowest elevation where Richardson number exceeds 0.25 is taken as the top of the boundary layer in the model, which is generally around 400–500 m in this case. Simulated hourly rainfall rate is also presented in Fig. 13f to illustrate the relationship between precipitation and the budget terms. Since the magnitude of subgrid-scale horizontal moisture convergence (SHF) was one to two order of magnitude smaller than that of SVF in the average, and thus will not be discussed.

In general, during the development of the MCS A, large values of resolvable grid-scale horizontal moisture flux convergence and vertical moisture flux divergence occurred throughout the lower troposphere (Fig. 13a–b). Shortly after MCS A moved inland at 0100 UTC 30 May, the HF maximum occurred below 500 m and reached a value of $240 \times 10^{-8} \text{ kg m}^{-3} \text{s}^{-1}$ which was about twice of that in the stage of MCS A development over the ocean. The significant vertical moisture flux divergence below 500 m in Fig. 13b indicated that grid-scale processes were major contributor to carry water vapor upward away from the boundary layer. Negative VF in the lower atmosphere (below 1600 m) and positive VF above 7000 m imply an upward vertical moisture transport in the middle atmosphere. It is consistent with the distribution of vertical velocity with magnitude around $30\text{--}50 \text{ cm s}^{-1}$ at the level between 6000 and 8000 m (Fig. 13d). The maximum vertical velocity at about 0300 UTC 30 May lagged the second VF maximum by 1–2 h because vertical velocity was likely enhanced by

Fig. 13. Height-time cross sections of area averaged moisture budget terms ($10^{-8} \text{ kg m}^{-3} \text{ s}^{-1}$) over MCS A for 5-km-resolution grid in QUIK run valid during the period 1500 UTC 29 May – 0900 UTC 30 May 2001 for (a) horizontal moisture flux convergence (HF), (b) vertical moisture flux convergence (VF), (c) local rate of change of water vapor (LC), (d) vertical velocity (w in cm s^{-1}), (e) subgrid-scale vertical flux convergence (SVF) and (f) simulated rainfall rate (mm h^{-1})

topography when MCS A moved further inland and got closer to the CMR. Terms HF and VF were similar in magnitude but opposite in sign.

This is understandable because HF can be approximated by the product of moisture and horizontal divergence (i.e., $\nabla \cdot (\bar{V}_H \bar{q}) \approx \bar{q} \nabla \cdot (\bar{V}_H)$)

because the moisture field is quite uniform in the environmental southwesterly flow and hence the horizontal advection term of q in the decomposition of HF is relatively small. Similar arguments can be applied to VF because vertical velocity, and hence vertical advection, is relatively small in the boundary layer. Since the horizontal and vertical divergences are similar in magnitude due to the continuity equation, HF and VF also had similar magnitude.

Although intense horizontal moisture flux convergence appeared, LC changed only slightly (Fig. 13c). Nevertheless, positive values of LC occurred in the lower troposphere before the beginning of heavy precipitation, which indicates that water vapor was accumulated locally before the convection initiation. After the convective precipitation occurred, however, LC decreased significantly in the layers between surface and 7000 m. There are two episodes of large simulated rainfall rate at around 21–22 UTC 29 May and 2–3 UTC 30 May (Fig. 13f), which were associated with two intense precipitation produced by the MCS A over the ocean and over land, respectively. In both episodes, maximum simulated rainfall rate occurred 1–2 h after the HF maximum appeared, and as discussed in the last paragraph the second rain maximum was probably enhanced by topography.

The height-time cross section of SVF in the boundary layer (Fig. 13e) illustrates that the subgrid-scale processes near surface transport water vapor upward when convective precipitation occurs although with a relatively small magnitude. A larger negative value of SVF near surface occurred before and during MCS A developed over the ocean. It indicates that the subgrid-scale disturbances helped to carry more water vapor upward from the ocean surface. On the other hand, the fluctuation in the magnitudes of SVF also reveals the turbulence characteristics of the boundary layer over land. The contribution from the residual term S in the boundary layer was relatively minor and its magnitude was about $10 \text{ kg m}^{-3} \text{ s}^{-1}$ when MCS A developed over the ocean, and increased to about $20 \text{ kg m}^{-3} \text{ s}^{-1}$ when the MCS A moved inland (not shown). The positive values of S likely attributes to evaporation from rain droplets and this process further moisten the boundary layer.

5.3 Discussion

The moisture budget terms HF, VF and SVF were integrated from surface up to the cloud base to examine the moisture transport processes in the subcloud layer during the evolution of MCS A. Since the cloud water vapor mixing ratio in the COAMPS simulations was in general larger than zero above 500 m throughout the time of diagnosis, this height was taken as the cloud base. The moisture budget terms were further averaged within the 3 h prior to convection (1500–1700 UTC 29 May), during the convection over the ocean (while maximum simulated precipitation center was over the ocean, i.e., 1800 UTC 29–0000 UTC 30 May), during convection over land (while maximum simulated precipitation center was over land, i.e., 0100–0600 UTC 30 May), and also within the 3 hours afterwards (0700–0900 UTC 30 May). The schematic diagrams of the integrated moisture budgets in the subcloud layer associated with the evolution of MCS A is illustrated in Fig. 14., where upper and lower panel was derived from 5-km to 15-km resolution simulation results, respectively.

For the 5-km resolution (Fig. 14a), the terms $\text{HF}_{0-500\text{m}}$ and $\text{VF}_{0-500\text{m}}$ [hereafter terms (A) and (B), respectively] indicate weak horizontal moisture flux convergence of value $2.4 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ and weak vertical moisture flux divergence of value $-2.5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ in the subcloud layer prior to the convection. However, after MCS A started to develop over the ocean, both the horizontal moisture flux convergence ($29.5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) and the vertical moisture flux divergence ($-25.1 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) increased significantly. Both terms (A) and (B) further increased when MCS A moved over Taiwan. During the MCS A development, the subcloud layer was characterized by strong resolvable grid-scale horizontal moisture flux convergence which is consistent with the observational study of Chen (1979) for a Meiyu frontal case. The magnitudes of horizontal moisture flux convergence below 850-hPa in Chen's case was about $30 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ as compared to the value of $62.5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ in the lowest 500 m in the present case when MCS A moved and intensified over land. For comparison, Fuelberg et al. (1986) obtained a value of $200 \times$

Fig. 14. Schematic diagram of moisture budgets ($10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) before, during and after convection for MCS A development in the (a) 5-km and (b) 15-km resolution QUIK run. The terms (A) and (B) represent integrated (below cloud base) grid-scale horizontal and vertical moisture flux convergence, respectively. Term (C) is the integrated (below cloud base) subgrid-scale vertical moisture flux convergence, with the one for the 15-km grid further decomposed into turbulent (C_1 , same as C for the 5-km grid) and cumulus convective transport (C_2). Term (D) is surface evaporation estimated by the integrated (below 10 m) subgrid-scale moisture flux convergence

$10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ below 900 hPa for an intense MCS case over central Oklahoma, which was about three times of that in the present study.

As discussed in the last section, the grid-scale vertical moisture flux in the subcloud layer was enhanced by orographic effect to transport more

water vapor into the convection and produced more precipitation in areas west of the CMR at southern Taiwan. To estimate this quantitatively, the vertical moisture flux convergence in the subcloud layer due to orographic lifting was calculated based on the flux of q in Eq. (1) ($(V_H \cdot \nabla h)q$). The area of calculation was where orographic rain estimation using wind field at 500 m was over 0.1 mm, and this also concentrated at the western side of CMR similar to that for 850 hPa but with smaller area. Then this orographic VF term was also integrated from surface up to 500 m as for VF_{0-500m} . It was found that during the period of 0100–0600 UTC 30 May when MCS A was over land, the average integrated VF due to orographic lifting contributed $-12.2 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ to the total value of VF_{0-500m} that was $-49.4 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ (i.e., $\sim 24.7\%$ contribution). Although this does not seem to be a large contribution, it should be noted that gradient of CMR's topography increases rapidly with height and hence orographic rain estimation aloft the cloud base (e.g., that for 850 hPa in Fig. 12) was much larger than that in the boundary layer. Therefore, orographic effect contributed a considerable amount of rain especially in southwestern Taiwan during the development of MCS A over land but was not dominating the subcloud layer moisture flux convergence.

In the mean time, the subgrid-scale vertical moisture flux convergence, SVF_{0-500m} (hereafter term (C)), had a small value of $-0.38 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ prior to convection. It increased substantially to $-5.1 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ and $-13.6 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ while MCS developed over the ocean and over land, respectively. The ratio of $(C)/((B) + (C))$ had a value of 16.9% over the ocean and increased to a value of 21.6% over land during the period of MCS development, indicating that disturbances under 5 km played a more important role in the total upward moisture transport as MCS developed over land than that over the ocean. Evaporation was estimated by integrating subgrid-scale vertical moisture flux convergence below 10 m, i.e., SVF_{0-10m} [hereafter term (D)]. It had a small value of $-0.34 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ prior to convection. Although evaporation term (D) was relatively small compared to the other budget terms, the ratio of $(D)/((B) + (C))$ indicates that the evaporation over the ocean surface

contributed 11.8% to the total amount of water vapor transported by grid-scale and subgrid-scale processes from subcloud layer into the MCS A. This was much higher than that during other stages of convection evolution. It is also noteworthy that in the COAMPS simulation a large sea surface latent heat flux occurred over the southern Taiwan Strait before the development of MCS A (not shown), indicating that the interaction between the atmosphere and the ocean was important for the initiation of MCSs. Similar results was observed in Liu et al. (2002) that an increase of surface latent heat flux appeared to be strongly related to the initiation and development of MCSs over the ocean. After convection, all the terms (A), (B), (C) and (D) decreased to values smaller than those during convection.

For the 15-km resolution, results are presented in Fig. 14b. Because of the cumulus parameterization scheme used in this domain, subgrid-scale processes in the 15-km resolution run included both turbulent and cumulus convective transport. Thus, term (C) in Fig. 14b can be further decomposed into two terms: vertical moisture flux transported due to turbulence that can be approximated by the corresponding subgrid term in the 5-km grid (C_1), and that due to the cumulus convective transport (C_2).

During various stages of MCS A development, both HF and VF derived from the 15-km resolution results (terms (A) and (B) in Fig. 14b) showed smaller values than those derived from the 5-km grid (terms (A) and (B) in Fig. 14a). As would be expected, SVF derived from the 15-km grid (term (C) in Fig. 14b) had larger values than that derived from the 5-km grid (term (C) in Fig. 14a). Quantitatively, the subgrid-scale transport in the 15-km resolution run accounted for 27.2% of total moisture flux (ratio of $(C)/((B) + (C))$ in Fig. 14b) when MCS A developed over the ocean, in which 19% was from disturbances under 5 km (ratio of $(C_1)/((B) + (C))$ in Fig. 14b) and 8.2% was from cumulus convective transport (ratio of $(C_2)/((B) + (C))$ in Fig. 14b). When MCS A moved over land, the percentage of subgrid-scale transport increased to 34.7% and the partition between sub-5-km disturbances and convective transports became 21.1% and 13.6%, respectively. Apparently, disturbances under 5 km was dominating for both MCS development over the ocean and land. Also, the relative contribu-

tion from cumulus convective transport was larger over land than over the ocean presumably due to stronger updrafts and downdrafts in the subcloud layer over land.

The surface evaporation term (D) (i.e., the subgrid term of SVF_{10m}) estimated from the 15-km resolution grid was slightly less than that from the 5-km fine grid. Absolute value of evaporation was much higher over the ocean surface than over land as would be expected. The ratio of $(D)/((B) + (C))$ computed in the 15-km grid indicated a percentage of 11.3%, which was much higher than the corresponding percentage in the other stages of MCS evolution. Thus, although the amount of evaporation was relatively small as compared to subgrid-scale disturbances and cumulus convective transports, it played a relatively important role before convection initiation over the ocean than that during the development of convection over the ocean and over land.

6. Summary and concluding remarks

In this study, numerical simulations using the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) were performed to investigate a heavy rain event associated with mesoscale convective systems (MCSs) along the Meiyu front over Taiwan area during 29–30 May 2001. MCS A, which was the focus of this study, developed over the southern Taiwan Strait along the surface Meiyu front at 1800 UTC 29 May. It slowly propagated toward Taiwan in the subsequent hours and produced heavy rainfall with a maximum 6-h accumulated rainfall of 120 mm in southern Taiwan. Large amount of water vapor was transported by the prefrontal southwesterlies in the lower troposphere and significant horizontal moisture flux convergence was observed along the front. Examination of the vertical variation of moisture flux convergence derived from Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses and QuikSCAT oceanic winds indicated that the moisture flux convergence during the development of the MCSs most likely originated from the boundary layer.

COAMPS simulations were performed in three nested domains with horizontal resolutions of 45, 15 and 5 km, respectively. The simulations covered 54-h period with four 12-h data assimilation cycles and used NOGAPS forecast fields as ini-

tial and lateral boundary conditions. In addition to CTRL run experiment, the QUIK run experiment was conducted with QuikSCAT oceanic winds blended into the initial conditions of every 12-h assimilation cycle. Moisture budget analyses were carried out to reveal moisture transport processes associated with the convection evolution using the simulation results. The major results can be summarized as follows:

- (1) Both the CTRL and QUIK runs simulated correctly the synoptic-scale conditions as well as the position of the Meiyu front. The QUIK run simulated better the magnitude of the low-level horizontal moisture flux convergence and reproduced better precipitation in terms of both amount and spatial distribution especially along the Meiyu front over the Taiwan Strait.
- (2) Orographic rain estimation indicated that precipitation associated the MCS when it developed along the Meiyu front (the Meiyu mode) continued until about 0300 UTC 30 May. Afterwards when the MCS propagated inland, orographic lifting effect took place and this contributed rain mostly to areas just west of the CMR in southern Taiwan (the orographic mode).
- (3) For the 5-km resolution runs, the MCS evolution was better simulated in the QUIK run as compared to that of the CTRL run. Also, QUIK run showed higher ETS values (i.e., higher forecast skill) in precipitation than that of CTRL run.
- (4) The grid-scale horizontal moisture flux convergence and upward vertical moisture flux divergence represented the major contribution for moisture transport in the subcloud layer in all stages of MCSs evolution, and their values increased substantially during the convection development.
- (5) In the upward transport of water vapor into the cloud base, subgrid-scale disturbances with respect to the 5-km grid had greater contribution over land than over the ocean. It helped to transport 21.6% and 16.9% of total moisture upward into convection developed over land and over the ocean, respectively.
- (6) The subgrid-scale vertical moisture flux convergence in the subcloud layer was further decomposed into that contributed from distur-

bances under 5-km and cumulus convection by comparing the corresponding subgrid-scale terms from the 15-km grid and the 5-km grid. It was found that transport from disturbances under 5-km was dominating the subgrid-scale processes for both MCS development over land and over the ocean. Also, the relative contribution from cumulus convective transport was larger over land than over the ocean presumably due to stronger updrafts and downdrafts in the subcloud layer over land.

- (7) Compared to the other moisture budget terms, surface evaporation had a small value but it played a relatively important role in the upward moisture transport processes before the development of MCS over the ocean.

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