A Numerical Study of a Mesoscale Convective System over the Taiwan Strait

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ABSTRACT

On 7 June 1998, a mesoscale convective system (MCS), associated with a mesoscale cyclone, was initiated on the south side of a mei-yu front near Hong Kong and developed over the Taiwan Strait. In this study, numerical simulations for this event are performed using the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5). The model captures the evolution of the MCS, including the shapes of clouds and the rainfall rate.

In the mature phase of the simulated MCS, the MCS is composed of several meso-β- and meso-γ-scale convective clusters possessing comma-like shapes similar to that of a midlatitude occluded cyclone. The cluster at the head of the “comma” consists of convective clouds that are decaying, while the tail of the comma is made up of a leading active convective line. A mesoscale cyclone, associated with a mesolow, at the tailing region of the leading convective line is well developed below 500 hPa. At 850 hPa, a mesoscale low-level jet (mLLJ) is located on the south side of the mesolow, and is directed toward the comma-shaped convective clusters. At 300 hPa, a mesohigh develops over the leading cluster. A mesoscale upper-level jet (mULJ) is located on the east side of this mesohigh. Relative streamline and trajectory analyses show that the mLLJ, associated with low $\theta_e$ and sinking air motion, is a rear-inflow jet, while the mULJ is the outflow jet of the MCS. Monsoon air from the boundary layer in front of the MCS feeds deep convection within the MCS.

Momentum budget calculations are performed in the regions of the mLLJ and mULJ, at the developing and mature stage of the MCS. The pressure gradient force and the horizontal advection are the main contributors to the development of mLLJ in the developing stage. Although the effects of the pressure gradient force are weakened considerably when the MCS reaches maturity, the horizontal advection continues to accelerate the mLLJ. Vertical advection tends to decelerate the mLLJ both in its developing and mature stages. The pressure gradient force and vertical advection are responsible for generating the mULJ in the early stages, and maintaining the mULJ in its mature stage. Strong convective upward motion, which carries the horizontal momentum upward, from the exit of the mLLJ to the entrance of the mULJ, is crucial in the vertical coupling of the mLLJ and mULJ.

1. Introduction

The rainy season over East Asia is called “mei-yu” in China, “baiu” in Japan, and “changma” in Korea. From May to mid-June, the mei-yu front is present in southern China. It shifts to central China and Japan from mid-June to mid-July, and then moves to Korea by the end of July. Rainfall during the mei-yu season is a major water resource for the East Asian region; however, heavy precipitation (often over 100 mm day$^{-1}$) can also cause severe flooding. The mei-yu front is one of the most important circulation systems for the hydrological cycle in the East Asia monsoon region.

The mei-yu front is a quasi-stationary front characterized by a weak temperature gradient, but a strong equivalent potential temperature ($\theta_e$) gradient (Tao...
A synoptic-scale low-level jet (LLJ) is usually located along the south side of the mei-yu front, at the northwestern periphery of the western Pacific subtropical high (Chen and Yu 1988). Recent studies based on satellite images showed that most of the heavy precipitation during the mei-yu season is created by mesoscale convective systems (MCSs) embedded within the mei-yu front (Fang 1985; Ninomiya et al. 1988a,b; Li et al. 1993). These MCSs are well organized and tend to move from west to east. Some of them are accompanied by mesoscale cyclones in the lower troposphere when they are fully developed (Akiyama 1984a,b). Due to the lack of mesoscale observations, the mesoscale structure and characteristics of these MCSs are not well understood.

The rapid progress of mesoscale models provides an effective tool to study MCSs along the mei-yu front. Kuo and Anthes (1982) showed that a mesoscale model with simple physics and smooth initial conditions could simulate many realistic features associated with the mei-yu front. Additional studies have shown that if the synoptic environment is favorable for the development of mesoscale circulations, the mesoscale circulation systems can be simulated in a numerical model initialized with routine synoptic-scale observations (Anthes et al. 1982; Chen et al. 1998, 1999, 2000). The physically consistent, four-dimensional model can provide us with an opportunity to examine the mesoscale features of the MCSs.

The LLJ associated with the mei-yu front has been studied using both observational data and numerical simulations. Based on observations in Japan, Matsumoto and Ninomiya (1971) suggested that the LLJ was a result of the downward transport of horizontal momentum from the upper-level jet (ULJ) by cumulus convection. Other studies argued that simple momentum exchange could not account for the directional change between the westerly ULJ and the south-southwesterly LLJ (Chen et al. 1994; Nagata and Ogura 1991). Based on the results of a two-dimensional model, Chou (1986) hypothesized that the LLJ formed by Coriolis acceleration of northward ageostrophic motion, in the convectively induced and thermally direct mesoscale secondary circulation in the subtropics. Nagata and Ogura (1991) conducted a modeling study of an intensive MCS along the baiu front. They simulated a localized LLJ with a horizontal scale of \( \approx 500 \) km associated with a mesoscale low. The localized LLJ was accelerated by the pressure gradient force toward the convectively induced low. Kato (1998) studied the maintenance and enhancement of the LLJ in the simulation of a torrential rain case over Japan. He found that the core of the localized LLJ is maintained through a balancing act between the acceleration of the pressure gradient force and the deceleration of the horizontal advection. Vertical advection decelerates the LLJ by transporting horizontal momentum upward, as convection develops. From an analysis of vorticity in the same case, Davison et al. (1998) found that the ageostrophic wind caused by convection helps to maintain and accelerate the LLJ, which in turn supports the convection, via the moisture supply.

More recently, Chen et al. (1998, 2000) found that, in addition to the synoptic-scale jets (LLJ and ULJ), mesoscale wind streaks associated with an intense mesoscale convective system are also present. Specifically, a mesoscale low-level jet (mLLJ) around 850 hPa and a mesoscale upper-level jet (mULJ) between 200 and 300 hPa appeared in a simulation of a mei-yu MCS system over central China, on 12–13 June 1991. Questions include the following: How representative are these features of other MCSs along the mei-yu front? And how do they form?

Du and Cho (1996) noted that the properties of the mei-yu front vary from season to season, and even from sector to sector during the same season. The front is mainly baroclinic before the spring-to-summer seasonal transition, and becomes mainly barotropic thereafter (Chen 1993). There are also large differences in stability and baroclinity between the eastern and western parts of the mei-yu front. Kato (1985) showed that, even before the seasonal transition, the southwestern sector of the mei-yu front has a near barotropic structure with a weak horizontal temperature gradient, but a strong horizontal wind shear, in the lower levels. Further studies indicated that the MCSs change their character when they travel from the western to eastern part along the same mei-yu front (Iwasaki and Takeda 1993). The mechanisms for the development of MCSs along the mei-yu front could be different in different sectors and seasons.

Due to the sparse observation, the dynamic structures of MCSs along a mei-yu front are not understood as well as those that take place in North America (Brandes 1990; Skamarock et al. 1994; Bartels and Maddox 1991; Trier et al. 2000a,b). Therefore, a question such as, “Do the MCSs along a mei-yu front have the same characteristics as those in North America?” remains unanswered.

In this paper, numerical simulations are carried out for an MCS (0000 UTC 7 June 1998) that developed along the mei-yu front over the South China Sea (SCS), and matured in the Taiwan Strait. The evolution of this system is simulated reasonably well using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (Penn State–NCAR) Mesoscale Model (MM5) with parameterized convection. The objective of this work is to study the structure of the MCS, as simulated by the model. In particular, we will assess the robustness of the mLLJ and mULJ as salient features of mei-yu mesoscale convective systems, as described in Chen et al. (1998, 2000). Specifically, we would like to know whether similar mesoscale wind streaks can be simulated in this case. If so, how do they form (e.g., where do they get momentum?) and what is the relationship between the mesoscale convection and other mesoscale features?

The model and the experimental design are outlined...
in section 2. The synoptic setting and an overview of the model simulation are described in section 3. Section 4 shows the mesoscale features of the simulated MCS, which is followed by the momentum budget diagnosis in section 5. Finally, a summary and discussion are given in section 6.

2. Model description and experimental design

The MM5 is a nonhydrostatic, primitive equation model with a terrain-following sigma ($\sigma$) vertical coordinate. The reader is referred to Dudhia et al. (1998) for a more detailed description of the model. In our simulations, the Grell et al. (1994) scheme is used to represent subgrid-scale cumulus convection. The mixed-phase microphysics scheme of Reisner et al. (1998) is used to represent subgrid-scale cumulus convection. The mixed-phase microphysics scheme of Reisner et al. (1998) is used to represent the moist process on the resolvable scale. Blackadar’s high-resolution PBL scheme (Zhang and Anthes 1982) is used to calculate the subgrid-scale vertical fluxes of sensible heat, moisture, and momentum.

Global analyses of the National Centers for Environmental Prediction (NCEP) Aviation (AVN) Model with 1.25° resolution are used as the model first guess field and boundary conditions. The daily 1° resolution Reynolds and Smith (1994) sea surface temperature analysis from NCEP is also incorporated into the model first guess field. The initial conditions for MM5 are obtained by objectively analyzing the observational data available on the Global Telecommunication System (GTS). GTS data include conventional surface and upper-level observations, as well as satellite-retrieved wind and temperature information.

The computational domains consist of a 54-km grid with a mesh size of $64 \times 76$ (D01), an 18-km grid with a mesh size of $97 \times 121$ (D02), and a 6-km grid with a mesh size of $121 \times 121$ (D03). All grids have 23 levels in the vertical. Domains D02 and D03 are nested within domains D01 and D02 using a two-way interaction method (Dudhia et al., 1998), and the lateral boundary condition of D01 is taken from the analyses. Figure 1 shows the domains and the conventional rawinsonde network. The average separation between upper-air stations over southern China is about 250 km, which is sufficient to resolve meso-$\alpha$-scale features in the initial field. However, the scarcity of rawinsonde stations over the SCS and the Taiwan Strait allows only synoptic-scale circulation systems to be resolved in the upper-air analyses. The simulations for D01 and D02 are initialized at 0000 UTC 7 June 1998, and integrated for 36 h. Domain D03 is activated at $t = 12$ h (equivalent to 1200 UTC June 7 1998), using the 12-h output of D02 as the initial field, and is integrated for 24 h. No cumulus parameterization is used in D03. Other than that, the physical parameterization schemes are identical among the three meshes.

3. Synoptic setting and overview of model simulation

At the initial time (0000 UTC 7 June 1998), a wind shear line extended from southern China to the south of Taiwan at 850 hPa (Fig. 2a). A synoptic LLJ with several wind streak centers (horizontal wind speed exceeding 10 m s$^{-1}$, shown in shaded area) embedded in it was located to the south of the wind shear line. One of the wind streak centers was associated with a meso-$\beta$-scale convective system (shaded area in Fig. 2b) at the SCS, which was the subject of this study. A zone of high-$\theta_e$ (> 346 K) air at 700 hPa, in which the MCS was embedded, can be found over the SCS immediately off China’s southern coast (Fig. 2b). The mei-yu frontal zone, with a $\theta_e$ gradient of about 8 K 100 km$^{-1}$, can be identified to the north of Taiwan along 25°N at 700 hPa. It was positioned 200–300 km north of the convergence line at 1000 hPa (Fig. 2d), indicating a shallow and northward-slanting frontal structure. A band of positive vorticity was found on the cyclonic shear side of the LLJ (Fig. 2c), with a maximum $4.96 \times 10^{-5}$ s$^{-1}$ located to the east of Hong Kong. A mesoscale vortex associated with convection, located at 22°N, 113°E, was analyzed at 1000 hPa using the higher-density surface observations. The minimum sea level pressure was 1007 hPa (Fig. 2d). Due to the scarcity of rawinsonde observations, the mesoscale features were not evident in the 850- and 700-hPa wind and $\theta_e$ fields. The synoptic environment where the MCS subsequently formed and developed included the following features: a low pressure center near the surface to the south of the mei-yu front at 700 hPa, a mesocyclone with a local vorticity maximum and a high-$\theta_e$ tongue at 700 hPa, and a synoptic-scale LLJ at 850 hPa. These features provide favorable conditions for the development of mesoscale convection (Tao 1980).

During the subsequent 24 h, the observed MCS over the northern SCS propagated eastward along the mei-yu front, and developed into a mature MCS over the Taiwan Strait by 1200 UTC 7 June. The mature MCS then crossed Taiwan and moved to the northwestern Pacific by 0000 UTC 8 June. The satellite infrared cloud-top brightness temperature ($T_b$) is used to illustrate its evolution. At 0000 UTC 7 June, a nearly circular meso-$\beta$-scale MCS (designated as M1), was located at 21°N, 115°E with a diameter of 200 km (Fig. 3a). Eighty kilometers to the south, there was another meso-$\gamma$-scale MCS (designated as M2) that exhibited a narrow south-to-north cloud field. During the subsequent 6 h, MCS M1 moved slower than MCS M2, but both expanded to the east, and then merged (Fig. 3b). Several embedded meso-$\gamma$-scale features with $T_b < -74^\circ$C formed and dissipated within the general M1 and M2 region, so it is hard (and not meaningful) to trace individual elements such as M1 and M2 after they merged. However, the merged MCS system continued to develop and display a comma shape. After 0900 UTC (Fig. 3c), the tail of
the comma-shaped MCS accelerated to the northeast, and it reached Taiwan at 1500 UTC (Fig. 3d). Meanwhile, the head of the comma-shaped MCS moved to the south of Taiwan. Despite the continued evolution of individual convective cells, the whole MCS maintained its comma shape. By 1800 UTC (Fig. 3e), the northern part of the MCS dominated southern Taiwan and resulted in heavy precipitation in this case. Meanwhile, a new meso-$\gamma$-scale convective center was generated over southern Taiwan, while the southern part of the MCS continued to move to the east. After 2100 UTC, the whole MCS had begun moving out of Taiwan (Fig. 3f).

From here on, we will designate the whole meso-$\alpha$-scale convective system as the “MCS,” and the meso-$\beta$- or meso-$\gamma$-scale convections embedded in this MCS as the “convective cluster.”

Most of our subsequent discussion is based on the results of the 6-km simulation, such as detailed structure of the mature MCS. However, some of the discussion, such as the evolution of the simulated MCS, its trajectory, and momentum analysis, is based on the 18-km simulation, which covers a bigger domain to better capture the evolution of the system. Considering the interaction of the two-way nesting grids used in this study, the 6-km grid effectively controls the simulation on the 18-km grid over the regions where these two grids overlap.

The simulated 500-hPa radar reflectivity at $t = 13$, 15, and 17 h (valid at 1300, 1500, and 1700 UTC 7 June 1998, and representing the period when the simulated MCS reached its mature stage) is shown in Figs. 4a, 4c, and 4e, respectively. To provide a qualitative comparison, we show the observed $T_b$ (brightness temperature) satellite images at 1000, 1200, and 1400 UTC 7 June 1998 in Figs. 4b, 4d, and 4f. Generally speaking, the 18-km MM5 simulates the evolution of this MCS reasonably well, despite some apparent discrepancies. The simulated MCS is displaced about 100 km to the north of the observed system (based on the satellite $T_b$ image). Moreover, there is a 3-h delay compared with the observations, possibly due to the precipitation spinup problem. The precipitation spinup problem occurs because there is little mesoscale information in the initial upper-air analysis over the region where the MCS formed, which means that the model needs several hours to recover mesoscale wind, temperature, and moisture structures that are responsible for the development of the MCS (Molinari and Dudek 1992). For instance, the MCS simulated in the model at $t = 13$ h (valid at 1300 UTC 7 June; Fig. 4a) is located at approximately 22°N, 117°–119°E. Its relative location and the comma shape correlate well with the observed satellite $T_b$, at 1900 UTC 7 June 1998 (Fig. 4b). At $t = 15$ h (valid at 1500 UTC 7 June), the 10-dBZ contour reaches Taiwan (Fig. 4c), with its location is similar to that of the 1200 UTC $T_b$ observation (Fig. 4d). Thus, the evolution of the simulated MCS is slower compared with the observation and its location remains displaced 100 km to the north from the observed system. At $t = 17$ h (valid at 1700 UTC 7 June), the northern part of the simulated MCS
Fig. 2. Model initial condition for D01. (a) The 850-hPa geopotential height (solid lines, contour interval of 20 gpm), temperature (dashed lines, contour interval of 2°C), and wind barb vectors at full barb for 5 m s⁻¹. Shaded areas are for horizontal wind speed greater than 10 m s⁻¹. Double-dashed line represents wind shear line. (b) The 700-hPa equivalent potential temperature \( \theta_e \) (solid lines, contour interval of 2 K). Observed satellite brightness temperature lower than \( 2548 \) K is shaded. (c) The 700-hPa vertical component of relative vorticity [solid (positive) and dashed lines (negative) for \( 2.0 \times 10^{-5} \) s⁻¹ contour interval] and wind vectors. (d) Streamlines at 1000 hPa and sea level pressure (dashed lines for 1-hPa contour interval).

(Fig. 4e) moves more slowly than the southern part, similar to the observed system. The relative positions of these cloud signatures and their eastward movements match the observed \( T_b \) at 1400 UTC (Fig. 4f). We admit that with an 18-/6-km model using parameterized convection and explicit moisture scheme, the model could not simulate the detailed structure and the evolution of individual meso-\( \gamma \)-scale convective clusters. However, we believe the simulation of the larger-scale aspects of the MCS is of sufficient accuracy for us to gain insights into the structure and development of this convective system.

Heavy rain occurred over the Taiwan Strait between 0900 UTC 7 June and 1200 UTC 7 June 1998 (Fig. 5a). Fortunately, Special Sensor Microwave Image (SSM/I) observation recorded two hourly rainfall centers both with a maximum of 25 mm at around 0942 UTC. Due to a 3-h delay, hourly rainfall at \( t = 13 \) h (valid at 1300 UTC 7 June) from the 18-km (D03) simulation is plotted for comparison with the SSM/I hourly rainfall record at 0942 UTC (Fig. 5b). In general, the area enclosed by the 1-mm contour of simulated precipitation correlates well with the region enclosed by the 5-mm contour of the observed. Two rainfall centers are also simulated in model, and have maximum values of 21 and 28 mm, respectively. The loci of all these centers are similar to those of the observed; except that the northern rainfall center is simulated about 60 km northwest of the observed, and the southern one is 20 km farther to the west than the observed. In spite of these discrepancies, the overall model results are quite encouraging.

4. Mesoscale features of an MCS in its mature stage

The simulated MCS reaches its mature stage over the Taiwan Strait at \( t = 15 \) h. At this time, the topographic
influence on the MCS is relatively weak. In the following section, we will discuss the mesoscale features of the MCS as simulated by the 6-km MM5 at $t = 15$ h.

a. The MCS, mLLJ, and mesolow

Figure 6a shows the simulated 850-hPa wind and height fields at $t = 15$ h. The geopotential height contours show a mesolow with a minimum height of 1450 gpm. A convective cluster A is embedded within the mesolow, while another cluster B is located just to the southeast (Fig. 6a). Several meso-$\gamma$-scale convective clusters are positioned to the south and north of B and act as a leading convective line together with B. Based on the satellite images of this MCS and the model simulation, one might attempt to associate the M1 and M2 observed cloud clusters (at 0600 UTC 7 June) with the simulated cloud clusters of A and B (at 1500 UTC 7 June). As we discussed earlier, these are transient convective systems, and it is not possible to make definite statement on the representation of simulated cloud clusters. Perhaps, one should treat them as generic systems, representing salient features of an MCS system that possesses a comma shape. A mesoscale low-level jet
Fig. 4. (a), (c), (e) Simulated radar reflectivity at \( t = 13, 15, \) and \( 17 \) h (every 10 dBZ) at 500 hPa of the D02 run. (b), (d), (f) Observed \( T_b \) at 1000, 1200, and 1400 UTC 7 Jun 1998 from satellite. The area of \( T_b \) lower than \(-74^\circ\)C is shaded dark gray and the area of \( T_b \) between \(-54^\circ\) and \(-74^\circ\)C is shaded gray.

(mLLJ), with a maximum horizontal wind speed of 25.6 m s\(^{-1}\), is located between clusters A and B. The axis of the mLLJ curves cyclonically to the southeast of the mesolow. Strong convergence occurs at the exit of the mLLJ (Fig. 6b), with a horizontal scale of 100 km. The maximum convergence reaches \(-40.4 \times 10^{-5} \) s\(^{-1}\). Positive vorticity centers are found at the mesolow, and on the left side of the mLLJ. Negative vorticity appears at the right side of the mLLJ (Fig. 6c). The vorticity and divergence centers are collocated at the mesolow and convective cluster A.

At 850 hPa, the mei-yu front with strong gradient of \( \theta_e \) is lying along 24.5°N, approximately 150 km north of the MCS and the mesolow. In contrast, convective clusters A and B are associated with high-\( \theta_e \) (>348 K) centers (Fig. 6d). It is interesting to note that a relatively lower \( \theta_e \) belt (<348 K) is present to the south of the mesolow, along the mLLJ. Vertical velocity at 850 hPa
indicates this low-$\theta_e$ belt is associated with descending motion at the rear and center of the mLLJ (Fig. 6e). Strong upward motion occurs over the high-$\theta_e$ area, which coincides with the convective clusters.

A mesolow at the surface is also associated with the MCS in the simulation (Fig. 6f). The central sea level pressure has dropped to 1004 hPa from 1007 hPa at the initial time. The wind field at the surface clearly shows a meso-$\alpha$-scale cyclone with a horizontal scale of $\sim$250 km. The entire MCS, including convective clusters and mLLJ, is embedded within this meso-$\alpha$-scale cyclone. Wind vectors reveal three distinct airstreams: one from the southwest, one from the south, and one from the northeast. This airflow structure is very similar to that of a midlatitude occluded cyclone (Kuo et al. 1992), even though the horizontal scale of this meso-$\alpha$-scale cyclone is much smaller than that of a midlatitude occlude cyclone. Cloud cluster B is located in a region where air from the south meets cooler air from the southwest forming a relative strong temperature gradient (e.g., resembling a cold front). Cloud cluster A is located at the center of the meso-$\alpha$-scale cyclone associated with relative cool temperature. It might be caused by the evaporation cooling effect near the boundary layer. The mLLJ, shown by the hatched area with horizontal wind speed greater than 14 m s$^{-1}$, is weaker and located farther to the north than the mLLJ at 850 hPa. There is a mesoscale high simulated on the north side of cluster B at the surface. This mesohigh is a very shallow system; it becomes much weaker at 850 hPa (Fig. 6a). As will be shown later, vertical motion at 925 hPa displays weak subsidence over the mesohigh (Fig. 9a).

The MCS in our case occurs 200–300 km south of the synoptic mei-yu front at 700 hPa, as shown in the 700-hPa $\theta_v$ field (Fig. 2b). A mesoscale cyclone and an mLLJ are the salient features associated with this MCS, during the mature stage in the lower troposphere. The mLLJ appears as the cold-air branch of the cyclone, which carries low-$\theta_e$ air from the middle troposphere, and descends to the surface. Strong divergence (upward motion) occurs at the exit of the mLLJ. The dynamic structure of the mLLJ is quite different from that of a synoptic-scale LLJ, which has upward (downward) motion left (right) of its exit region and right (left) of its entrance region. Figure 6e shows that downward (upward) motion occurs in the entrance (exit) of mLLJ. Many studies suggest that synoptic-scale LLJs during the mei-yu season transport moisture to convection (Chen and Yu 1988; Chen 1983; Ding 1992; Ninomiya and Murakami 1987). However, the mLLJ in our case is associated with the stream of relatively low-$\theta_e$ air. The descending stream of low-$\theta_e$ air has been found as the rear inflow jet, both in observations and in cloud-resolving numerical simulations of asymmetric midlatitude squall lines in North America (Houze et al. 1989; Brandes 1990; Skamarock et al. 1994; Davis and Weisman 1994). What is the role of this relative dry mLLJ in this case? Is it a rear inflow jet? Where do the low-$\theta_e$ air parcels come from? And, furthermore, where does the MCS obtain its moisture supply to produce heavy precipitation? These questions will be addressed in later sections.

b. The MCS, mULJ, and mesohigh

The height contour of 9700 gpm at 300 hPa exhibits an “Ω” like pattern over the MCS (Fig. 7a), with a closed mesohigh of 9705 gpm. Using composite and scale-separation analysis, Maddox (1980) found a similar mesoscale high in the upper troposphere, over a composite of the mesoscale convective complexes (MCCs) in North America. Upper-level west-southwesterly wind dominates over the MCS and the surrounding area. An mULJ, with a wind speed maximum of 23.1 m s$^{-1}$, is located to the east of the mesohigh; while a relative low wind speed core (<7 m s$^{-1}$) is located to its west (Fig. 7a). This couplet of high–low wind cores has a scale of $\sim$200 km. The wind vectors are nearly perpendicular to the height contours, indicating that the winds are highly ageostrophic. The pressure gradient force is nearly parallel to the wind vector on the east side of the mesohigh, suggesting that the mULJ is being accelerated by the pressure gradient...
Fig. 6. Simulated 850-hPa and surface mesoscale features from D03 run at $t = 15$ h (valid 1500 UTC 7 Jun 1998). Gray-shaded areas are the radar reflectivities greater than 40 dBZ, which represent the convection within the simulated MCS. (a) The 850-hPa geopotential height (solid lines, contour interval of 10 gpm), wind vectors, and isotachs (dashed lines, contour interval of 6 m s$^{-1}$). (b) The 850-hPa divergence field with $10 \times 10^{-5}$ s$^{-1}$ contour interval. Solid lines are divergence greater than or equal to zero; dashed lines are for that lower than zero. Hatched area is horizontal wind speed greater than 24 m s$^{-1}$, which delineates the mLLJ. (c) The 850-hPa vertical component of relative vorticity. Solid lines are vorticity greater than or equal to zero with every $20 \times 10^{-5}$ s$^{-1}$; dashed lines are for that lower than zero with a $10 \times 10^{-5}$ s$^{-1}$ contour interval. Hatched area is as in (b). (d) The 850-hPa equivalent potential temperature $\theta_e$ with a 1-K contour interval (solid lines). Hatched area is as in (b). (e) The 850-hPa vertical velocity. Solid lines are vertical velocity greater than or equal to zero with a 20 cm s$^{-1}$ contour interval; dashed lines are for that lower than zero with a 10 cm s$^{-1}$ contour interval. Hatched area is as in (b). (f) Sea level pressure (solid lines at 1-hPa contour interval), surface temperature (dashed lines at 1-K contour interval), and horizontal wind vectors. Hatched area is horizontal surface wind speed greater than 14 m s$^{-1}$. 
force. This is an important factor in the maintenance of the mULJ, which will be discussed in section 5. Conversely, the low wind speed core to the west of the mesohigh is decelerated by the westward pressure gradient at the west side of the mesohigh. If we subtract the mean winds in the domain of Fig. 7a from the simulated winds, the mesohigh is colocated with a divergent flow center at 300 hPa (Fig. 7b). The couplet of high–low wind speed cores in Fig. 7a becomes the two main outflow centers. The center of the mesohigh in this study, accompanied by a high-$\theta_e$ area (Fig. 7b), is located approximately 80 km to the east of the mesolow at 850 hPa. Strong upper-level divergence is simulated at the entrance region of the mULJ, between the high–low wind speed couplets (Fig. 7c). Its maximum value reaches $53.9 \times 10^{-5}$ s$^{-1}$. This divergence area is right above the mesoscale convergence at the exit region of the mLLJ (Fig. 6b). There is a second, weaker divergence center associated with cluster A, farther to the west. The maximum vertical velocity at 500 hPa reaches...
151.8 cm s\(^{-1}\) (Fig. 7d). It should be pointed out that there is no mesohigh or mesolow at 500 hPa. A high-\(\theta_e\) area appears to be associated with the MCS at 500 hPa (Fig. 9c). It appears that the mesoscale vortex exists from the surface up to the midtroposphere, behind the leading convective clusters. This structure is similar to a mesoscale convective vortex (MCV) developing in the stratiform region of an asymmetric squall line in earlier observations (Brandes 1990) and numerical studies (Skamarock et al. 1994) in North America. Furthermore, similar results were reported from climatological studies (Bartels and Maddox 1991; Trier et al. 2000a,b).

The shaded area of 30 dBZ at 300 hPa reflects cluster B, not A (Fig. 7a). It suggests that meso-\(\beta\)-scale convective clusters embedded in the MCS can be in differing stages of development, even when the whole MCS is becoming mature. The convective cluster “B” is in the developing stage, with convection extending up to 300 hPa, strong upward motion at 500 hPa, and divergence at 300 hPa. Meanwhile, convective cluster A is in a decaying stage, with weaker upward motion at 500 hPa and divergence at 300 hPa. The propagation of MCS is a manifestation of new convective clusters, continuously forming at the east side of the MCS (Ninomiya et al. 1988a,b).

c. Verification of mLLJ and mULJ

Analysis of the simulation shows that the mLLJ and mULJ form concurrently with the development of the MCS. After 3–6 h of model integration, an mLLJ and an mULJ have already appeared at 850 and 300 hPa, respectively (figures not shown). The way these mesoscale jet streaks evolve is similar to the simulations of Chen et al. (1998, 1999). At the mature stage, the maximum wind speeds of the mLLJ (850 hPa) and mULJ (300 hPa) are 26 and 24 m s\(^{-1}\), respectively. A couplet of high–low wind speed cores is a salient mesoscale feature found in the upper troposphere over the simulated MCS.

An important question is: Can these mesoscale wind field features be verified? The 6-h interval soundings and hourly rainfall observations at Tung-Kang (location plotted in Fig. 4a) provide useful information for model verification (Fig. 8a). From 0000 UTC 7 June to 1200 UTC 8 June, two rainfall episodes occur at Tung-Kang. All the winds are southerly or southwesterly. Note that the wind speed at 200 hPa increases before each rainfall episode and subsequently decreases. This is consistent with the simulated mesoscale high–low wind speed cores found in the upper troposphere. Furthermore, the wind speed at 700 hPa increases by about 4–5 m s\(^{-1}\) during each rainfall episode.

To provide a comparison, hourly simulation at a grid point RE (location plotted in Fig. 4a) is shown in Fig. 8b. The location of RE is selected because its position relative to the simulated MCS is similar to that of Tung-Kang relative to the observed MCS, taking into consideration that the simulated MCS is 100 km farther to the north and its development is delayed by 3 h compared to the observed MCS. It is interesting that two rainfall episodes also occur at RE. The wind speed of RE at 200 hPa (700 hPa) also increases (decreases) before each rainfall episode and decreases (increases) after that. The oscillations of 200- and 700-hPa wind speed curves are in opposite phase during the whole rainfall process. This wind speed change during precipitation implies that the mULJ (mLLJ) is ahead (behind) the convection. The similarity in the evolution of wind speed variations between Tang-Kang and RE provides support for the realism of these mesoscale wind field structures, although admittedly this is not an exact verification of the simulated features.

d. Airflow and trajectories relative to the MCS

To provide a comprehensive depiction of the three-dimensional airflow around the MCS, wind fields relative to the moving MCS are calculated using 6-km-resolution output. As described above, convective clusters, an mLLJ, and a mesolow are components of the MCS that are embedded within the meso-\(\alpha\)-scale cyclone. The moving speed of the MCS is estimated based on the moving speed of the cyclone at the surface. Relative streamlines around MCS at the surface and 850, 500, and 300 hPa at \(t = 15\) h are given in Fig. 9.

The relative streamline at the surface shows the structure of the MCS, with cluster B being the active, leading convective line, and A being the weakening convection cluster downwind of the active line. Airflow entering into leading convective cluster B originates from the east, in front of the MCS (Fig. 9a). Strong upward vertical motions are collocated within the convective clusters. It should be noted that there are a few areas of downward vertical motion within the MCS. One area, with a maximum value of \(-15.4\) cm s\(^{-1}\), is located to the north of convective cluster B, which is associated with the mesohigh in Fig. 6f. Another area of downward motion is located to the south of the MCS, which is associated with the mLLJ (Fig. 6a). It is interesting to note that the relative streamlines spread out divergently near the ocean surface from the center of the downward motion associated with the mLLJ. This divergent, near-surface flow is similar to the airflow at the rear of a squall line observed in North America (Newton 1966; Houze et al. 1989).

At 850 hPa, the cyclonic circulation associated with the meso-\(\alpha\)-scale cyclone is very apparent. High relative wind speed can be identified at both the north and south sides of the mesolow (Fig. 9b). The relative streamlines suggest that the mLLJ to the south of the mesolow is not the only inflow entering the cyclone at lower levels. There is an apparent inflow from the north, but this inflow is counteracted by the mean southwesterly flow and, therefore, is not apparent in the absolute wind plots (Fig. 6a).
Figure 9c shows the relative streamlines and $\theta_e$ at 500 hPa. Air parcels inside the MCS come largely from the lower levels with high equivalent potential temperature, and rising motion is prominent within the MCS (Fig. 7d). However, the synoptic-scale airflow at 500 hPa appears to originate from the northwest of the MCS. This airflow splits as it encounters the MCS, moves around the MCS, and then recombines at the southeast of the MCS [a similar airflow pattern was found at midlevel by Johnson and Bartels (1992) in their study of an MCS case over Kansas and Oklahoma on 23–24 June 1985, based on radar observation].

At 300 hPa (Fig. 9d), similar separation of the synoptic-scale flow around the MCS can be seen, but the outflow from the MCS in the upper level appears to prevent the synoptic flow from recombining. The mesohigh appears to be the source of airflow, which fans out to the east.

From the discussion above, the inflow of this MCS originates from the lower troposphere or planetary
boundary level, below 850 hPa in front of the MCS, with outflow to the southeast of the MCS at 300 hPa. The mLLJ, acting as a storm-relative, rear inflow jet, does not inject warm, moist air into the MCS directly as the LLJ. Rather, the mLLJ serves as the descending low-$\theta_e$ air branch that helps lift the high-$\theta_e$ air from the east, assisting the development and eastward propagation of leading convective cluster B near the surface. The mLLJ also entrains low-$\theta_e$ air into the mesolow and convective cluster A at 850 hPa, which might contribute to the weakening of this cluster.

Figure 10 shows the vertical cross section of several fields along the line $XX'$ from the 6-km domain output (location of cross sections is shown in Fig. 6a). This cross section passes through the mLLJ at 850 hPa, the mULJ at 300 hPa, and convective cluster B (see Fig. 6a). The relative horizontal wind field along the $XX'$ cross section reveals an mLLJ at the rear of the MCS.
Fig. 10. Vertical cross section through XX’ (location is plotted in Fig. 6a) from D03 run at \( t = 15 \) h (valid 1500 UTC 7 Jun 1998). (a) Simulated relative wind vectors and horizontal wind speed of the MCS parallel to the vertical cross section along line XX’; solid lines are for relative wind speed from X to X’ (southwesterly) with a 2 m s\(^{-1}\) contour interval; long-dashed line is zero relative wind speed contour; short dashed lines are for relative wind speed from X’ to X (northeasterly) with every 2 m s\(^{-1}\) contour interval. Shaded areas are the radar reflectivity greater than 40 dBZ and represent the convection within the simulated MCS. (b) Simulated equivalent potential temperature (solid lines with a 1-K contour interval) and relative wind vectors along XX’. Simulated vertical velocities greater than 80 cm s\(^{-1}\) are plotted as thin dashed lines every 40 cm s\(^{-1}\). Thick dashed line is the zero temperature contour. Light gray areas are relative humidity greater than 95%, and dark gray area are relative humidity equal to 100%, representative of cloud within the simulated MCS.

below 500 hPa, and a mULJ in front of the MCS between 200 and 400 hPa (Fig. 10a). The maximum relative wind speeds are 13.5 and 7.8 m s\(^{-1}\) for mLLJ and mULJ, respectively. The axis of the mLLJ starts at 600 hPa from the southwest, goes down slantwise to 850 hPa, and then penetrates into convective cluster B. Another convective cell, which is in an early developing stage, is located farther to the northeast of cluster B. The vertical wind shear in the region of the convection is rather weak. Strong upward motion appears in front
of the mLLJ and rearward of the mULJ, with a maximum of 218 cm s$^{-1}$ within the convective cluster at 400 hPa (Fig. 10b). Weak downward motion occurs along and under the axis of the mLLJ. It should be noted that there is a clear indication of "inflow" below 900 hPa to the east of the MCS, which is the moist inflow mentioned above. The axis of the mLLJ is associated with a belt of low $\theta_e$ (Fig. 10b). Figure 10b shows that the middle-level monsoon air with low $\theta_e$ enters the MCS from the rear. This air is subject to rainwater evaporation and is negatively buoyant, and so it continues to descend. It finally spreads out near the ground (also shown in Fig. 9a). One branch flows back to the west, and one goes to the east encountering the warm, moist inflow from the east, and creating a sharp $\theta_e$ gradient at the rear of the leading convective line. This, in turn, helps maintain the convection by forcing this warm, moist air upward. This flow pattern suggests the following conclusions: 1) moist air from the east is the primary convective inflow; 2) the mLLJ and mULJ are the lower-level rear inflow jet and upper-level outflow jet of the MCS, respectively; and, 3) convection and its associated vertical motion might act as a coupling mechanism between these two mesoscale jets in the mature stage.

The structure of the MCS along the XX’ cross section is quite similar to that of several classical squall lines observed in North America (Newton and Newton 1959; Houze et al. 1989; Brandes 1990). Newton and Newton (1959) emphasized that downward motion at the rear of the squall line transfers westerly momentum in the rainy area to produce a rapid eastward movement of the low-level convergence area. The MCS in this study moves as fast as a squall line (the advective speed of which varies between 10 and 15 m s$^{-1}$ in Houze (1993)), with an averaged speed of 11.5 m s$^{-1}$ from $t = 13$ h to $t = 17$ h. The mLLJ also plays an important role in the eastward propagation of this MCS.

A selection of representative air parcel trajectories, moving relative to the MCS, are calculated using results from the 18-km domain simulation, to permit a longer time history. These trajectories provide an illustration of the mesoscale Lagrangian vertical circulations around the MCS. Four significant airstreams are identified using representative trajectories (Fig. 11). Trajectory L1 is

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**Fig. 11.** Simulated relative trajectories from the D02 run. Radar reflectively greater than 40 dBZ at 850 hPa at $t = 15$ h is shaded to represent the convection within the simulated MCS. (a) Relative trajectories come from the lower level at $t = 10$ h to $t = 20$ h in 1-h intervals. Geopotential height is plotted at every two time steps (in km); the location of the air parcel at $t = 15$ h is signed with larger symbols than the other time steps. The large L is the locus of the mesolow. (b) Relative trajectories form $t = 10$ h to $t = 20$ h of synoptic flow around MCS in the middle level. Geopotential height is plotted at every two time steps (in km); the location of the air parcel at $t = 15$ h is signed with larger symbols than the other time steps. (c) Same as in (b) but for the upper level. The large H is the loci of mesohigh.
traced backward from the core of the mULJ at 300 hPa, at \( t = 15 \) h. It originates on the west side of the mLLJ at 1.87 km at \( t = 10 \) h (Fig. 11a) and climbs to 9.72 km at \( t = 15 \) h, with a slight anticyclonic curvature and an average rising speed of 43.6 cm s\(^{-1}\). It is nearly saturated from the very beginning, reaches saturation at 559 hPa at \( t = 13 \) h, and flows out of the cloud at 300 hPa at \( t = 15 \) h.

Trajectory L2 is calculated both backward and forward from convective cluster B at 850 hPa at \( t = 15 \) h, which provides an example of convective inflow air. It starts from the east of the MCS at 0.47 km in the boundary layer at \( t = 11 \) h, moves westward into the convective cluster B at \( t = 14 \) h, then turns northward and rises rapidly within the convection, while moving southeastward from \( t = 15 \) h (1.47 km) to \( t = 18 \) h (8.15 km) with a maximum upward speed of 102 cm s\(^{-1}\) at \( t = 16 \) h. This parcel begins with a relative humidity of 90% and reaches near saturation after \( t = 17 \) h. We note that the potential vorticity increases sharply during the 2-h period from \( t = 15 \) h to \( t = 17 \) h, when PV jumps from 0.42 to 2.5 PVU (potential vorticity units), as the parcel rises from 850 to 474 hPa. Presumably, this is close to the level of maximum condensation heating in the cloud, which also corresponds to the level of maximum vertical motion (Fig. 10b).

Trajectory L3 is also calculated backward and forward from mLLJ at 850 hPa at \( t = 15 \) h. It originates from the boundary layer at 0.47 km in the mLLJ at \( t = 11 \) h, with a maximum descending speed of 22 cm s\(^{-1}\) at \( t = 14 \) h. The air parcel becomes drier from 11 (with relative humidity of 98.3%) to 14 h (with relative humidity of 90.0%) as it descends to the lower levels. After parcel L3 reaches the rear of the leading convective line, it turns to the north. It leaves the convective cluster after \( t = 17 \) h and finally flows around the mesovortex, gradually ascending to midlevels.

Trajectory L4 provides another sample of an air parcel coming from the north of the cyclone. It starts from north of the cyclone at 891 hPa at \( t = 10 \) h with large vorticity \( (18.6\times10^{-5}\text{ s}^{-1}) \) and rises gradually around the cyclone, finally reaching 627 hPa on the south side of the cyclone. It does not intersect the mLLJ. Several air parcel samples flowing from the north (not shown) do not fan out like the case described in Chen et al. (1998). This trajectory implies that the air parcel from the north, as a whole, does not sink and become involved with the mLLJ. Instead, the sinking parcel in the mLLJ originates from the monsoon air to the southwest of the cyclone.

The results become more interesting when we start to examine the air parcel trajectories in the middle and upper levels. Rising motion is prominent within the MCS, indicating that air parcels inside the MCS originate from the lower levels. However, the ambient flows at midlevel become separated as they encounter the MCS. These flows are diffusent (confluent) upstream (downstream) of the MCS (Fig. 11b). This flow pattern is also evident in the streamlines analysis at 500 hPa (Fig. 9c). In the upper troposphere, similar separation of the ambient flow is seen near the MCS, but there is no confluence downstream of the MCS at upper levels.

(Fig. 11c).

The results of this trajectory study are different from the simulation of an MCS along the mei-yu front over eastern China (Chen et al. 1998). For the system over eastern China (as shown in Chen’s et al. study), the MCS formed along the mei-yu front, and the trajectories in the cold air from the north fanned out on the north side of the front, encountered the southwesterly warm air, and produced strong convergence along the front. Previous studies on severe rainstorms along the mei-yu front conclude that the intrusion of dry air from the northern middle layer flew into the convective system, and, therefore, the evaporative cooling effect of raindrops are important for the formation and maintenance of heavy rainfall (Tsuboki and Asai 1995; Nagata and Ogura 1991). On the other hand, Kato (1998) suggested that, “Since entire layers were saturated over the mei-yu frontal zone and \( \theta_e \) was larger than that on both sides, raindrops hardly evaporated.” According to his study, “dry air from the north did not reach the rainband that developed south of the frontal zone.” Examination of a 1996 rainfall case along the mei-yu front in Japan, by Kato et al. (1998), further demonstrated that no intrusion of dry air into the rainband was found. In the present study, it is noted that the MCS is located 200–300 km from the synoptic 700-hPa mei-yu front. The MCS develops in a barotropic, warm, moist environment of southwesterly monsoon flow from the surface to the upper levels. Based on the trajectory analysis, it is also evident that the cold dry air from the north of the mei-yu front never gets into the MCS. Convection is maintained by the lifting of warm, moist, boundary layer air with high \( \theta_e \) from the east and by the descending and drier mLLJ (which is a rear-inflow jet relative to the MCS) from the southwest. This structure is similar to squall lines observed in the past (Newton 1966; Houze et al. 1989; Brandes 1990).

5. Momentum budgets of mLLJ and mULJ

In order to understand the maintenance and generation of mLLJ and mULJ, each term of the momentum budgets from the D02 (18 km) run was output during the model integration. We now present the results of momentum budgets.

a. Technical scheme

The horizontal momentum flux equations in MM5 are given by...
horizontal divergence of momentum (HDM) flux,

\[ \text{UHDM} = - \frac{1}{p^*} \left[ m^2 \left( \frac{\partial_p \overline{u}/m}{\partial x} + \frac{\partial_p \overline{v}/m}{\partial y} \right) \right] \]  

vertical divergence of momentum (VDM) flux,

\[ \text{UVDM} = - \frac{1}{p^*} \frac{\partial_p u\overline{u}}{\partial \sigma} \]  
\[ \text{VVDG} = - \frac{1}{p^*} \frac{\partial_p v\overline{v}}{\partial \sigma} \]  

pressure gradient force (PGF),

\[ \text{UPGF} = - \frac{1}{p^*} \left[ \frac{mp^*}{\rho} \left( \frac{\partial_p u}{\partial x} - \frac{\sigma}{p^*} \frac{\partial_p v}{\partial x} \right) \right] \]  
\[ \text{VPGF} = - \frac{1}{p^*} \left[ \frac{mp^*}{\rho} \left( \frac{\partial_p v}{\partial y} - \frac{\sigma}{p^*} \frac{\partial_p u}{\partial y} \right) \right] \]  

Coriolis force (COR),

\[ \text{UCOR} = f v - e w \cos \theta \]  
\[ \text{VCOR} = -f u + e w \sin \theta \]  

Since the equations are further simplified if we only consider the momentum budget along the jets axis, there is a motivation to transform horizontal momentum from the (x, y) coordinates into right-hand coordinates (S, N) with the S axis pointing from southwest to northeast along the axis of the lower- and upper-level jets. The momentum budget in the (S, N) coordinate can be obtained by the following transformation equation, using the momentum tendency equation as an example:

\[ \text{TMT} = \text{UTMT} \cos(\pi/4) + \text{VTMT} \sin(\pi/4). \]  

In the following discussion, the southwest to northeast momentum budget is calculated, because the mLLJ and mULJ run nearly in this direction (although the mULJ has a stronger westerly component).

b. Momentum budget in the mature stage of an MCS

Momentum budget calculations at 850 and 300 hPa show that the contribution of each term to the momentum budget is quite different in the exit and entrance regions, for both the mLLJ and mULJ (not shown). Area-averaged budgets are calculated separately for exit and entrance regions to distinguish their roles in the momentum budget. The areas of horizontal wind speed greater than 22 m s\(^{-1}\) at 850 hPa and 20 m s\(^{-1}\) at 300 hPa are regarded as the mesoscale jets, respectively. The exit and entrance areas of mLLJ and mULJ are naturally distinguished by the zero contour of HDM. Table 1 gives the area average of TMT, HDM, VDM, PGF, and COR terms, at the entrance and exit regions of the mLLJ at 850 hPa, and mULJ at 300 hPa.

The TMT at the exit of the mLLJ at 850 hPa is positive with an area average of \(2.93 \times 10^{-3}\) m s\(^{-1}\). The PGF and VDM decelerate the mLLJ at the exit region, with an average of \(-0.53\) and \(-1.33 \times 10^{-3}\) m s\(^{-1}\), respectively. Only the HDM tends to accelerate the mLLJ, with an average value of \(4.28 \times 10^{-3}\) m s\(^{-1}\) in the exit region, where the mLLJ is primarily dominated by the horizontal momentum advection effect. The total momentum tendency yields negative values at the entrance of the mLLJ. This is because, although PGF and COR increase the momentum, HDM decreases the momentum at the entrance region. The location of the mesoscale center shown in Fig. 6a can explain why the PGF acts to enhance the momentum along the S direction at...
the entrance region, but decrease that momentum at the exit region of the mLLJ. The exit region of the mLLJ is located predominantly to the east of the mesolow, while the entrance region is located to the west of the mesolow. The PGF acts to accelerate the southwest flow at the entrance region, but decelerates momentum at the exit region. The mLLJ, as a whole, intensified slightly, as shown in Table 1. This intensification is attributed to HDM and COR.

For the mULJ as a whole, the momentum tendency is rather small, with an area average of $-0.30 \times 10^{-3}$ m s$^{-2}$. The PGF is one of the main momentum contributors to the mULJ, because mULJ is located on the east side of the mesohigh, and air flows closely along the pressure gradient (Fig. 7a). Another main momentum contributor for mULJ is VDM. It is interesting to compare the VDM term at the exit region of mLLJ and the entrance region of mULJ, because heavy precipitation occurs in this area. From Table 1, the VDM is negative in the exit region of the mLLJ and positive in the entrance region of the mULJ. This suggests that the momentum is transported upward from the mLLJ to mULJ. The VDM term can be written as

$$VDM = -\frac{\partial u w}{\partial \sigma} \approx \frac{\partial u w}{\partial \sigma} \approx -\frac{\partial w}{\partial Z}. \quad (5.16)$$

If $u, w$ increases with height, the VDM should be negative. Conversely, if $u, w$ decreases with height, the vertical divergence of momentum flux should be positive. Figure 12 depicts the vertical flux of horizontal southwesterly momentum $(u, w)$ on cross section XX’ from D02 output. The $u, w$ exhibits a large column of upward momentum flux in the exit (entrance) of the mLLJ (mULJ), with a maximum value of $21.36 \times 10^{-3}$ m$^2$ s$^{-2}$ at about 400 hPa. The positive momentum flux area is coincident with the strong convection, and extends up to 300 hPa, which is the entrance level of the mULJ. The vertical flux of horizontal momentum $u, w$ increases with height at the exit of the mLLJ at 850 hPa, and decreases with height at the entrance of the mULJ in 300 hPa. Thus, the VDM helps to transport the southwesterly momentum from the exit region of mLLJ to the entrance region of mULJ, in this case. In other words, the horizontal momentum in the mLLJ is transported upward by resolvable-scale vertical motion to develop and sustain the mULJ. Kato (1998) also suggested that the horizontal momentum is transported to the midlayer through the vertical advection within the convection in a band-shaped, torrential rain case observed along the baiu front in Japan.

From the discussion above, the momentum budget of the mLLJ and the mULJ in their mature stage can be summarized as Fig. 13. Horizontal advection of momentum is the main contributor in accelerating the wind speed in the exit region of the mLLJ. The momentum gained is partly counteracted by the pressure gradient force and partly transported upward. In the entrance region, HDM acts to decelerate the mLLJ, but the PGF compensates for this loss and maintains the strength of mLLJ. For the mULJ, the PGF is the main contributor to the momentum budget both in the exit and entrance regions. In the entrance region, HDM acts to decelerate the mULJ, but it is compensated for not only by PGF, but also by VDM.

The budget study shows that strong horizontal momentum is produced by the convectively induced mesolow at the entrance of the mLLJ in the lower level through the pressure gradient force. It is not generated by the downward momentum transport from the upper

<table>
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<th>Momentum budget</th>
<th>Exit</th>
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<td>TMT</td>
<td>2.93</td>
<td>-0.76</td>
<td>1.23</td>
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<tr>
<td>PGF</td>
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</tr>
<tr>
<td>COR</td>
<td>0.47</td>
<td>0.29</td>
<td>0.39</td>
</tr>
</tbody>
</table>

TABLE 1. Momentum budget in the exit and entrance regions of mLLJ (850 hPa) and mULJ (300 hPa) at mature stage $t = 15$ h. Units are in $10^{-3}$ m s$^{-2}$.

FIG. 12. Simulated wind vector and vertical flux of southwesterly horizontal momentum (solid lines are for greater than or equal to 0 every $4 \times 10^{-3}$ m s$^{-2}$; dashed lines are for less than 0 every $2 \times 10^{-3}$ m s$^{-2}$) at $t = 15$ h along XX’ cross section. Hatched area is the horizontal wind speed greater than 22 m s$^{-1}$ at the lower level and 16 m s$^{-1}$ at the higher level, representative of mLLJ and mULJ. Gray-shaded areas are vertical velocity greater than 80 cm s$^{-1}$.
level. On the contrary, momentum is later transported to the exit of the mLLJ by horizontal advection, and then is brought upward to the upper level by vertical advection to maintain the mULJ. This vertical advection, in cooperation with the pressure gradient force induced by the convectively induced mesohigh, helps to generate and sustain the mULJ at the upper level.

We also calculated the momentum budget at the earlier stage of the MCS development ($t = 6\ h$). The pressure gradient force is the main component that accelerates the wind speed of the mLLJ and the mULJ at the developing stage. The horizontal advection term accelerates the mLLJ, but decelerates the mULJ. The vertical advection term causes the mLLJ to lose momentum to the mULJ. As shown in Fig. 13, momentum in the mLLJ is transported upward by resolvable-scale vertical motion to maintain the mULJ in its mature stage. It appears that this kind of vertical transportation has already taken place between the mLLJ and mULJ in their developing stage at $t = 6\ h$.

6. Summary and discussion

An MCS that formed over the South China Sea and developed over the Taiwan Strait on 7 June 1998 is studied using the Penn State–NCAR MM5, with triply nested grids (54, 18, and 6 km). The model is successful in simulating the evolution of the MCS, with the exception that the system’s position is about 100 km north of the observed system, and its timing for development is delayed by 3 h. The simulation (particularly with the use of the 6-km grid) provides us with an opportunity to examine the structure and evolution of this MCS event, using the high-resolution model data.

Figure 14 depicts a schematic diagram of the mature MCS, derived from the analysis of the simulation. There are several meso-$\beta$- and meso-$\gamma$-scale convective clusters embedded within the comma-shaped MCS, at its mature stage. Each of them is in a different stage of development. The convection at the head of the comma shape is weak and appears to be decaying; it is collocated with a meso-$\alpha$-scale cyclone, existing below 500...
hPa. Mesoscale cyclonic circulation is associated with a mesolow. The tail of the comma consists of deep convection, in its developing stage, that extends up to 200–300 hPa. A mesohigh, formed as a result of convection, can be found at 200–300 hPa on top of the developing convective clusters. The low-level circulation associated with the mesoscale cyclone, represented by southwesterly, southwesterly, and northeasterly flows at the surface, is very similar to that of a typical occluded cyclone in the midlatitudes. An mLLJ is located to the south of the meso-α-scale cyclone, pointing to the comma-shaped convection. An mULJ is located to the east of the mesolow in the upper level.

Three-dimensional, MCS-relative airflows are also summarized in Fig. 14. There are four main airflows at the mature stage of the MCS. Convective inflow with high $\theta_e$ comes from the east, in front of the MCS, and ascends very fast within the MCS while turning to the southeast cyclonically. It then flows out of the MCS at the upper level. Rear inflow with low $\theta_e$ originates from the midtroposphere. It descends to the rear of the leading convective line, first, and then turns northward after meeting with a moist, convective inflow. Finally, it ascends to the midlevel around the mesoscale cyclone at the north. The air parcel from the north of the mesoscale cyclone flows around the cyclone while rising, gradually, to the midlevels. Another airflow starts at the tip of the mLLJ, and climbs up to the upper level, flowing anticyclonically out of the MCS from its east side.

Relative streamline and trajectory study shows that the mLLJ, associated with low-θ, air and sinking motion, is a rear-inflow jet, while the mULJ is the outflow of the MCS. Convective moist inflow is caused by the monsoon air coming from the east, in front of the MCS, near the boundary layer.

From the very beginning, the MCS is associated with a meso-α-scale cyclone system. This cyclone is a shallow system that exists only in the lower troposphere, initially. The cyclone is intensified concurrently with the development of the MCS. The mesolow, mLLJ, and MCS are all embedded within the mesoscale cyclone as it travels along the southwesterly monsoon flow. Although the lower-level storm-relative circulation and cloud patterns possess a structure similar to those of an occluded cyclone at middle latitudes, the scale is much smaller. Moreover, unlike the midlatitude, occluded cyclone, this mesoscale cyclone can only be found below 500 hPa. In the upper troposphere, a weak mesohigh is located on top of the MCS, similar to the mesohighs found in midlatitude MCSs. However, the inner structure of the MCS at the mature stage is more like a midlatitude squall line, with a subsiding, storm-relative, rear inflow at the lower level, and a mesoscale vortex in the stratiform region, behind the leading convection line. The scale of the mesoscale vortex in this case, 250 km, is larger than the maximum scale range of the mesoscale vortex found in North America (e.g., 50–200 km) (Trier et al. 2000a). The structure and dynamics of this MCS–meso-α-scale cyclone system, associated with the mei-yu front, appear to be a hybrid between a midlatitude cyclone and a squall line.

Momentum calculations at $t = 6$ h and $t = 15$ h, when the mLLJ and mULJ are in their developing and mature stages, show that the mLLJ is generated by the pressure gradient force and horizontal advections. The mULJ is sustained by the pressure gradient force and the vertical transport of momentum, by resolvable-scale vertical motion. In the mature stage of the MCS, the contribution of pressure gradient force is rather weak in the lower troposphere, and the mLLJ, as a whole, is sustained by the horizontal advection term. While, the mULJ continues to receive momentum from the mLLJ through the vertical transport of momentum.

Although the model has produced many interesting mesoscale features associated with the simulated MCS, some features cannot be easily verified, due to a lack of mesoscale observations over the ocean. Further studies should focus on the physical processes responsible for the initiation and development of the MCS, mLLJ, and mULJ. Although mesoscale numerical models can provide useful insights into the structure and evolution of a mesoscale convective system, the need remains for data from special mesoscale field experiments to verify the results presented in this paper. Admittedly, with 18-/6-km grid and parameterized/explicit convection, the model could not reproduce the finescale structure of the meso-γ-scale cloud clusters. It would be desirable to perform simulations of a mei-yu MCS with a cloud-resolving model using explicit cloud microphysics.

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