A Cloud-Resolving Simulation Study on the Merging Processes and Effects of Topography and Environmental Winds

DANHONG FU

Laboratory for Cloud and Precipitation and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

XUELIANG GUO

Chinese Academy of Meteorological Sciences, Beijing, China

(Manuscript received 1 February 2011, in final form 12 October 2011)

ABSTRACT

The cloud-resolving fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) was used to study the cloud interactions and merging processes in the real case that generated a mesoscale convective system (MCS) on 23 August 2001 in the Beijing region. The merging processes can be grouped into three classes for the studied case: isolated nonprecipitating and precipitating cell merging, cloud cluster merging, and echo core or updraft core merging within cloud systems.

The mechanisms responsible for the multiscale merging processes were investigated. The merging process between nonprecipitating cells and precipitating cells and that between clusters is initiated by forming an upper-level cloud bridge between two adjacent clouds due to upper-level radial outflows in one vigorous cloud. The cloud bridge is further enhanced by a favorable middle- and upper-level pressure gradient force directed from one cloud to its adjacent cloud by accelerating cloud particles being horizontally transported from the cloud to its adjacent cloud and induce the redistribution of condensational heating, which destabilizes the air at and below the cloud bridge and forms a favorable low-level pressure structure for low-level water vapor convergence and merging process. The merging of echo cores within the mesoscale cloud happens because of the interactions between low-level cold outflows associated with the downdrafts formed by these cores.

Further sensitivity studies on the effects of topography and large-scale environmental winds suggest that the favorable pressure gradient force from one cloud to its adjacent cloud and stronger low-level water vapor convergence produced by the topographic lifting of large-scale low-level airflow determine further cloud merging processes over the mountain region.

1. Introduction

Cloud merger is a complex and nonlinear dynamical–microphysical process in which two adjacent convective cells tend to merge into a single cell, which was first documented at the Thunderstorm Project in Florida (Byers and Braham 1949).

Early observations indicated that a large cloud could be formed by the merging of several small neighboring cells, and the merged cloud entities might exhibit the characteristics of increased cloud diameters and cloud depths, which was postulated to be the main mechanism of producing large convective clouds (e.g., Ludlam and Scorer 1953; Scorer and Ludlam 1953; Malkus 1954; Malkus and Scorer 1955; Malkus and Riehl 1964; Changnon 1976; Lopez 1977; Simpson et al. 1971, 1980; Wiggert et al. 1981; Woodley et al. 1982).

The previous studies suggested that cloud merging could occur at different horizontal scales (Westcott 1977; Houze and Cheng 1977), and the commonly recognized features of a cloud merger are the combining of updrafts and a spreading and convergence of downdrafts, echoes, and precipitation areas (Malkus 1954; Westcott 1977, 1984; Simpson 1980; Tao and Simpson 1984, 1989). Mergers could also be categorized as first- and second-order mergers (Westcott 1977; Simpson 1980), with first-order mergers defined as the result of the joining of two or more previously independent echoes at the 1 mm h⁻¹ isopleth and second-order mergers as the product of the joining of two or more first-order mergers,
which are larger in size and last longer in time than the first-order mergers, and the mean rainfall rates usually increase (Westcott 1984; Simpson et al. 1993).

More rainfall could be produced by the merged convection than single-cell convection on tropical islands (Keenan et al. 1990; Simpson et al. 1993) and in the tropical ocean (Houze and Cheng 1977; Leary and Houze 1979; DeMott and Rutledge 1998), subtropical oceans (Simpson et al. 1971, 1980), and midlatitudes (Changnon 1976). In addition, the merging process was also found to have important effects on the production of severe weather, such as bow-echo weather (Carey and Rutledge 1998; Carey and Rutledge 2000; Finley et al. 2001; Takahashi et al. 2001; Lang and Rutledge 2002; Carey et al. 2003; Klimowski et al. 2004; Takahashi and Shimura 2004). However, some observations found that the merging processes could decrease damaging surface winds and convergence and suppress cloud circulations (Barnes 1978; Turpeinen and Yau 1981).

The cloud merging process was found to initiate by the formation of a cloud bridge linking two adjacent cells (e.g., Simpson 1980; Holle and Maier 1980; Cunning et al. 1982). The proposed mechanisms for cloud merging may be grouped into five categories: (i) low-level convergence (e.g., Hill 1974; Frank and Lhermitte 1976; Wilkins et al. 1976; Simpson et al. 1980; Simpson 1980; Holle and Maier 1980; Turpeinen and Yau 1981; Cunning et al. 1982; Turpeinen 1982; Cunning and DeMaria 1986; Tao and Simpson 1989; Westcott and Kennedy 1989), (ii) wind shear and downdraft interactions (e.g., Holle and Maier 1980; Simpson 1980; Simpson et al. 1980; Cunning et al. 1982; Miller et al. 1982; Turpeinen 1982; Tao and Simpson 1984; Peterson 1984; Cunning and DeMaria 1986; Rotunno et al. 1988; Weisman et al. 1988; Westcott and Kennedy 1989; Tao and Simpson 1989; Trier et al. 1997; Westcott 1994; Kogan and Shapiro 1996; Fu and Guo 2006), (iii) the pressure gradient between two cells at different stages (e.g., Orville et al. 1980; Bennetts et al. 1982; Turpeinen 1982; Tao and Simpson 1984, 1989), (iv) upper-level outflows (Rotunno et al. 1988; Weisman et al. 1988; Westcott 1994; Trier et al. 1997), and (v) different propagation speeds of two cells (e.g., Turpeinen and Yau 1981; Cunning et al. 1982; Turpeinen 1982; Tao and Simpson 1989; Westcott and Kennedy 1989; Kogan and Shapiro 1996; Lin and Joyce 2001).

These mechanisms may operate together or separately at different scales or stages of clouds during the cloud merging processes. The low-level convergence could be produced by large-scale lifting, wind shear, the pressure gradient force, or downdrafts associated with cold outflows. Interactions of downdrafts associated with cold outflows may play an important role in the merging processes for precipitating clouds, and the interaction of a storm cell’s cold surface outflow with the low-level shear could produce much deeper and less inhibited lifting than that without the low-level shear (Rotunno et al. 1988; Weisman et al. 1988; Trier et al. 1997). The pressure gradient force usually occurs at different strengths or at different growth phases of clouds, which might not be associated with cold outflows. The upper-level radial outflows from strong updrafts often form an upper-level cloud bridge for clouds in the maturing to dissipating stage at which the updraft core reaches higher elevations. In addition, the middle- and upper-tropospheric wind shears were found to be important to the updraft tilting and overall structure of cloud systems. The merging process, therefore, due to the upper-tropospheric radial outflow could be also affected by wind shear (Trier et al. 1997). The relatively small number of cell mergers was observed due to the different propagation speed of cells.

Previous numerical simulations, however, generally adopted idealized methods to initiate convection, which could not objectively reflect the natural cloud merging processes and could restrict the direct application of the results to natural cases. Some recent studies showed that factors such as wind shear, cold pools, and convective available potential energy (CAPE) are critical to forming and sustaining a convective system (Parker and Johnson 2004a,b; Weisman and Rotunno 2004; James et al. 2005). An appropriate description of these processes in a numerical model is necessary to study the cloud merging process. Most previous numerical simulations were carried out without considering the effects of topography and the large-scale environmental wind on cloud merging processes. In addition, the quantification of the effects of cloud interactions and merging processes on precipitation has significant and potential benefits in understanding the cell interactions responsible for precipitation enhancement via cloud seeding (e.g., Levy and Cotton 1984; Rosenfeld and Woodley 1993; Changnon et al. 1995; Czys et al. 1995; Guo and Fu 2003).

Mesoscale convective systems (MCSs) in the Beijing region were usually found to experience multiple merging processes before they formed to be larger and more persistent cloud systems. To clarify the realistic multiple merging processes in forming the MCSs is critical to the better understanding of the MCSs formation and the associated severe weather events. Therefore, the primary motivation of this study is to identify the realistic cloud multiple-merging processes and to investigate their formation mechanism in a realistic manner including the effects of topography and large-scale environmental wind. The numerical simulation studies of an MCS case on 23 August 2001 were conducted by using the cloud-resolving fifth-generation Pennsylvania State University–National...
Center for Atmospheric Research (NCAR) Mesoscale Model (MM5). A brief description of the simulation methodology and the synoptic conditions will be given in sections 2 and 3, respectively. Section 4 contains the results of the Doppler radar observations and the simulations of the cloud interactions and merging, the merging mechanisms, and the effects of the topography and the large-scale wind on the merging. The summary and conclusions will be given in section 5.

2. Methodology

Numerical experiments were performed using the version 3 of MM5 (MM5V3). The data for initial and boundary conditions were constructed from the global analyses of the National Centers for Environmental Prediction (NCEP) with 1° × 1° resolution. Two nested-grid domains were used in the current simulation, and the domain is centered at 40°N, 116°E (Fig. 1). Domain 1 has a resolution of 9 km with 100 × 100 grid points; domain 2 has a grid resolution of 3 km with grid points of 180 × 180; all domains have 37 vertical layers with a sigma level, and the horizontal and vertical resolution were sufficient to reproduce much of the mesoscale structure and evolution of squall-line-type convective systems (Weisman et al. 1997). The Schultz microphysics scheme (Schultz 1995) was used in both domains 1 and 2. The Blackadar scheme and the Rapid Radiative Transfer Model (RRTM) longwave scheme (Mlawer et al. 1997), which includes the use of all major absorbers and important trace species and the water vapor continuum model, were used for the parameterization of the planetary boundary layer. The U.S. Geological Survey (USGS) global land-use distribution in MM5 was used with a 2-min resolution in domain 1 and a 30-s resolution in domain 2. The lateral boundary conditions were relaxation/inflow–outflow. The simulation was performed from 0800 Beijing Standard Time (BST) 23 August to 0800 BST 24 August 2001.

To examine the effects of topography and the initial large-scale environmental wind on cloud merging processes, sensitivity tests were performed by setting the terrain height in domain 2 to zero and the horizontal winds at initial and boundary conditions in both domains 1 and 2 to zero.

3. The synoptic conditions

Figure 2 shows the environmental winds, temperature, and moisture at the surface on 23 August 2001. At 0800 BST (Fig. 2a), the Beijing area was dominated by southerly warm and wet airflow at the surface, and the air temperature exceeded 20°C and the maximum moisture reached about 15 g kg⁻¹. By 1200 BST (Fig. 2b), air
temperature had increased due to the solar radiation heating, and the southerly horizontal wind speed had also intensified, which increased the transport of the water vapor from south to north. The wind flow is depicted as ground-relative wind (the same hereafter).

Figure 3a–c display the distributions of CAPE and vertical shear from surface to 6 km at 1200 BST. It shows that the maximum CAPE exceeded 2000 J kg\(^{-1}\) in the study area (Fig. 3a), and the high value of CAPE corresponded well with high wind shear (Figs. 3b,c). Figure 3d is a skew T–log\(p\) and hodograph diagram in the vicinity of the initial clouds (41.75°N, 113.85°E) at 1200 BST. The sounding was characterized by moderate amounts of instability, and the hodograph exhibited a quasilinear structure, which indicated strong wind speed shear and weak directional shear at this stage. It is noted that there is substantial horizontal variability in water vapor and CAPE over the domain. The synoptic conditions were favorable for the initiation and development of the convective cloud (Tao and Simpson 1984; Wang and Randall 1994; Robe and Emanuel 2001; Stalker and Knupp 2003).

4. The merging processes and formation mechanisms

a. Observed behavior of convective cells and cloud merging processes

Because of the intrusion of a low vortex system located in the Mongolian region, a large number of isolated convective cells first formed over the northwestern mountain region of Beijing City located in northern China in the afternoon on 23 August 2001, and the isolated cells gradually merged and eventually formed a severe MCS that produced downbursts and hailstones (Fig. 4).
The convective cells observed by a Doppler radar at the Beijing Meteorological Station at 1457 BST (Fig. 4a) had obvious isolated characteristics with a maximum echo of around 45 dBZ and a horizontal scale of about 10–20 km. By 1539 BST (Fig. 4b), the isolated cells joined together and reflected an echo structure as cumulus clusters with several echo cores. The maximum echo increased to around 50 dBZ and the horizontal scale extended to about 50 km. A low-reflectivity bridge around 15 dBZ formed between clusters A and B.

At 1558 BST (Fig. 4c), the cloud clusters moved southeasterly and the horizontal scales also extended. By 1652 BST (Fig. 4d), the cloud clusters continued to move southeasterly, and clusters A and B weakened because of precipitation. By experiencing a similar merging process, the left-side cluster C formed with a maximum echo of about 50 dBZ. The cluster C was also linked with cluster B by a reflectivity bridge with reflectivity of about 15 dBZ at that time. By 1751 BST (Fig. 4e), cumulus clusters A and B merged together and the maximum echo intensified to about 50 dBZ. Cluster C developed and formed a bandlike echo and a maximum echo was around 45 dBZ. By 1900 BST (Fig. 4f), cluster C merged with clusters A and B, and the maximum echo increased to 50 dBZ. By 1955 BST (Fig. 4g), the cumulus clusters merged and formed the MCS with several echo cores or intensive centers, and the maximum echo was about 50 dBZ. By 2051 BST (Fig. 4h), the MCS moved southeasterly, during which the merging process of the intense centers was completed.

Based on the observed results described above, the merging processes could be categorized into three stages: single-cell scale (several to tens of kilometers in horizontal scale), cluster-scale merging (tens to several hundreds of kilometers), and echo-core merging within the MCS.

b. Simulated multiscale merging processes and formation mechanisms

To verify the modeling results, Fig. 5 displays the horizontal distribution of the precipitation intensity estimated from a Doppler radar at the Beijing Meteorological Station at 1651 BST, and that simulated by the
model at 1700 BST. It shows that the simulated overall structure of precipitation is well consistent with that observed. The maximum precipitation intensity of the radar reached about 48 mm h$^{-1}$, while that derived from the model exceeds 45 mm h$^{-1}$. The multicore structure of precipitation is also well captured by the simulation.

The definition of cloud merger is not unique. The previous studies (Westcott 1977, 1984; Simpson 1980; Tao and Simpson 1984, 1989) defined cloud physical merging as the result of the joining of two or more previously independent echoes at the 1 mm h$^{-1}$ precipitation isopleth at the surface. The dynamic merger was usually defined by the combination of the updraft (Westcott 1984). For the convenience of analyses, the merging process in this paper is defined to be the aggregation of neighboring clouds at the cloud outline of total hydrometeor mixing ratio of 0.1 g kg$^{-1}$ for cloud physical merging, and the joining of 45-dBZ echo isograms for echo cores or updrafts for dynamic merging since the area in high-echo core are consistent with that in updraft core at upper levels of the clouds.

The merging processes discussed in the following sections are merging between nonprecipitating cells, merging between precipitating cells, and echo-core merging.

1) THE MERGING BETWEEN ISOLATED NONPRECIPITATING CELLS

The merging processes between isolated nonprecipitating cells are characterized as the merging between independent cells with scales from several to tens of kilometers, which usually occurred at the initial stage of cloud formation. According to Fig. 3a, the CAPE in the area of these simulated clouds is about 750 J kg$^{-1}$. To better understand the merging process, two time stages of the merging processes at 1315 and 1330 BST are presented in Figs. 6 and 7. At 1315 BST (Fig. 6a), two cells, C_A and C_B, which are located over a northern mountainous region of Beijing, have a horizontal size of around 20 km and a maximum echo of around 35 dBZ. No precipitation at the surface is yielded for either cell at this moment. Thus, the merging process between the two cells will be grouped into nonprecipitating cloud merging, and the two neighboring cells are linked by a weak echo bridge of about 15 dBZ.

The horizontal perturbation pressure field at 4 km shows that C_B is located at the lower perturbation pressure area while C_A is in the higher perturbation pressure area, and the maximum magnitude of pressure perturbation deviations is about 0.4 hPa; therefore, the pressure gradient force from C_A to C_B acting at 45$^\circ$ to the westerly wind is produced at the level responsible for accelerating air parcels at upper levels from C_A to C_B, resulting in the merging of C_A with C_B. Since C_B is the older and stronger cell and C_A is the younger and weaker cell, the cloud merging from C_A to C_B is also in good agreement with that proposed by Orville et al. (1980).

The perturbation pressure structure at the surface, however, shows that the favorable pressure structure is not formed for enhancing the low-level convergence at this moment (Fig. 6b).

Figure 6c displays the vertical distribution of perturbation pressure along the line A1B1 denoted in Fig. 6a. It indicates that there are two high pressure centers, with the stronger one located in C_A and the weaker one in C_B, so that a strong upper-level pressure gradient force above 4 km directed from C_A to C_B is produced between the two cells, which can enhance the upper-level outflow from C_A to C_B.

The vertical echo and dynamic structure of the two cells is given in Fig. 6d. Isolated updrafts existed in C_A and C_B at this stage. The upper-level outflow generated from C_A is the main factor linking C_A with C_B by forming a weak cloud bridge between the two cells. The horizontal pressure gradient force from C_A to C_B can induce apparent airflow, efficiently transfer cloud particles from C_A to C_B, and further enhance cloud bridge formation at middle and upper layers between the two cells.

The entire region between C_A and C_B exhibits ascent at low levels, which is produced by the interactions of the topography and the large-scale, low-level airflow.

The cloud bridge consists of the supercooled cloud droplets and relative high fraction of snow at this stage. Therefore, the transport of snow precipitation particles...
from one cloud to another occurs (Fig. 6e). The effects of transport of snow precipitation particles may increase the precipitation efficiency and lightning rate in the seeded cell (Knupp et al. 2003) and also may enhance cloud merging processes due to the enhanced downdraft of the naturally seeded cell in the precipitating stage. The horizontal pressure perturbation in Fig. 7a shows a structure similar to that in Fig. 6a. But the pressure
structure at the surface shows that a favorable pressure structure forms for the surface air convergence below the cloud bridge (Fig. 7b). Two high pressure centers are formed at the locations nearer the area below the cloud bridge and the pressure gradient forces caused by them are favorable for the air convergence.

The perturbation pressure force tends to decrease at the lower levels, at which the merged clouds are well mixed at the bridge (Fig. 7c). There is only one high pressure center located in the upper levels of $C_A$, by which the pressure gradient force directed from $C_A$ to $C_B$ is maintained. The two cells develop and are still dominated by two independent updrafts, and the cloud bridge also develops (Fig. 7d).

The cloud bridge consists of supercooled cloud water, snow, and graupel at this stage (Fig. 7e). Comparing with that at 1315 BST (Fig. 6e), the graupel particles obviously increase in the cloud bridge at 1330 BST. The efficient transfer of the graupel particles may increase the number of graupel embryos and enhance precipitation in the down-shear cloud (Knupp et al. 2003).

To further elucidate the physics involved in the formation of the upper-level cloud bridge and transfer of cloud particles, and the dynamical processes that further
enhance the low-level pressure gradient favorable for the merging process, the vertical distributions of divergence and convergence fields, condensational heating, and water vapor mixing at 1315 and 1330 BST are shown in Fig. 8. Figure 8a shows that a convergent field dominates the low levels of the two cells while a divergent field dominates the upper levels of the cells. Between the two cells, there is a strong low-level convergence zone with high water vapor content beneath a stronger divergence zone at the middle and upper levels, which produces a condition favorable for the ascending motion of moisture air at the low level between CA and CB. The divergence zone located above the maximum updraft level of the vigorous CA produces the strong radial outflow (Foot and Wade 1982), which forms the initial weak upper-level cloud bridge. The vertical distribution of condensational heating (latent heating) calculated from temperature perturbation induced from water vapor phase change indicates that the transfer of cloud particles from CA to CB can induce the redistribution of the condensational heating between the two adjacent cells, which may destabilize the air at cloud bridge and further enhance the convergence at and below the cloud-bridge area and the subsequent merging process, which can be clearly seen in the subsequent development of the merging process (Fig. 8b). In comparing with those at 1315 BST in Fig. 8a, the cloud bridge further develops
and the low-level water vapor convergence is substantially enhanced below the cloud bridge at 1330 BST in Fig. 8b. Therefore, the mechanism of the nonprecipitating-cloud merging process can be attributed to the existence of a favorable upper-level pressure gradient force directed from one weaker and younger cell toward its neighboring old and stronger one, under which the cloud bridge originally formed by the upper-level outflow generated from one upwind cell to its downwind neighboring one can be persistently enhanced. The transfer of cloud particles due to the formation of the cloud bridge can induce the redistribution of condensational heating, which destabilizes the air at and below the cloud bridge and forms a favorable low-level pressure structure for low-level water vapor convergence and merging process, which leads to the final merging between the two non-precipitating cells.

2) MERGING BETWEEN PRECIPITATION CLOUDS

To discuss merging between precipitating clouds, two merging situations are presented here: the merging between a single precipitating cell and cluster, and the merging between clusters. Figure 9 shows the merging process between the precipitating single cell and cloud cluster at 1545 BST. The horizontal distributions of radar echo, wind vector, and cloud outline in Fig. 9a show that CL_A, which is formed through merging processes of isolated nonprecipitating cells of C_A, C_B, and new cells, has a horizontal scale of around 60 km in one direction, maximum radar echoes of 45 dBZ, and the maximum rainfall reaches 9.38 mm in the past 15 min. A strong isolated precipitating cell, marked as C_C, has a maximum echo of 45 dBZ and horizontal scale of around 15 km.
Figure 9b displays the vertical distribution along line CD in Fig. 9a. One of the prominent features in the figure is the formation of an upper-level weaker cloud bridge, by which the two cells are linked at upper levels. The wind vector field indicates that the upper-level outflow generated from CC is flowing to CLA. Both cells are well developed with maximum echoes located above and below the 0°C level, which reflects a large quantity of ice phase particles at the upper levels and high rain-water amounts below the melting level. Therefore, the cloud particles can be efficiently transported from CC to CLA by the upper-layer airflow and induce the redistribution of condensational heating and subsequent dynamic processes such as the enhanced low-level convergence and development of low-level merging processes, as discussed in the previous section.

Figure 10 shows the merging process between the cloud clusters at 1715 BST. Through various scale merging processes including the merging processes of isolated nonprecipitating cells, precipitating isolated cells, precipitating cells and clusters, and small-scale clusters and the quite similar merging mechanism discussed above, two main cloud clusters denoted CLb and CLc have been formed (Fig. 10a). Both clusters are at the mature phase with higher echo intensity and updrafts as well as intensive precipitation at the surface. The weaker cloud bridge can also be found at the upper levels between the two clusters (Fig. 10b). The apparent upper-level airflow from CLb to CLc is generated by the upper-level outflow of CLb and further enhanced by the westerly environmental winds. For the condensational heating, a similar distribution can be found in the merging processes between the precipitating clusters (Fig. 10b), which is favorable to the development of the cloud bridge and further merging process by enhancing the convergence at the low level.

The merging mechanisms between precipitating single cells and clusters, and that between cloud clusters are very consistent with those between nonprecipitating cells. The upper-level outflow is responsible for the formation of a cloud bridge by which two neighboring clouds are linked. The formation of the cloud bridge can redistribute the condensational heating and induce
subsequent dynamic processes, which further enhance the development of the cloud bridge and subsequent cloud merging processes. The strong low-level vapor convergence and favorable pressure gradient are the main factors that enhance the further merging processes of two adjacent clouds.

3) MERGING BETWEEN ECHO CORES WITHIN THE MCS

When the merging processes between cloud clusters have been completed, the formed mesoscale cloud system still has several separate cores (>45 dBZ), and the merging process between these cores can also be found. To clarify the mechanism responsible for core merging within the MCS, Fig. 11 presents the horizontal and vertical distributions of radar echo and wind vectors at 1900 BST. The horizontal distribution in Fig. 11a shows that the MCS contains many independent echo cores, and several echo cores are also linked with bridges. The vertical cross section along line GH is shown in Fig. 11b. It indicates that the ordered distribution of up- and downdrafts in the mesoscale convective cloud system corresponds with three centers with intensity over 45 dBZ, marked as C₁, C₂, and C₃. The three cores are bridged at low levels, and the strong low-level outflows induced by core downdraft are obvious. Differing from the formation mechanism of the upper-level cloud bridge, the low-level cloud bridge is produced by the interactions of the downdraft and outflow formed from high echo cores (Fig. 11b). Therefore, the outflow interactions generated from neighboring echoes are responsible for the merging of echo cores within the MCS. Knupp et al. (1998) inferred similar processes associated with the upscale development of a small MCS.

The analyses above indicate that the upper-level outflow is responsible for the formation of an upper-level cloud bridge by which two adjacent cells are linked. The low-level outflow interactions should be responsible for the echo-core merging within the MCS in the study region. Since the upper-level outflow is closely associated

Fig. 13. As in Fig. 12, but for the merging process without topography at 1615 BST. The downdrafts (dashed lines; contour interval is −1.0 m s⁻¹) are noted in (d).
with cloud intensity and environmental conditions such as upper- and low-level environmental winds, low-level convergence, and water vapor content (also strongly influenced by topography), the further clarification of the effects of environmental wind and topography on the merging process is necessary. Studies regarding the influences of topography and the large-scale environmental wind on cloud merging process are rarely found in the published literature. Since a real-case simulation study is conducted by using a cloud-resolving mesoscale model in this paper, it provides an opportunity to determine the possible effects induced by these factors.

c. The effects of topography on cloud merging processes

The sensitivity test without topography is performed and shown in Figs. 12 and 13. Figure 12a shows the horizontal distribution of radar echoes at 4 km AGL, wind vectors, and perturbation pressure at 1545 BST without the inclusion of topography. It indicates that without topography two relatively weak cells, labeled C_TA and C_TB, are formed, and no precipitation is occurring at this moment. Both cells are located at the high perturbation pressure area, which is quite different from that with topography in which one cell is located at the high perturbation pressure area and another cell is at the low perturbation pressure area (Fig. 6a).

The horizontal perturbation pressure at the surface in Fig. 12b shows that C_TA is located near a low pressure center and C_TB is near a high pressure center, which is not a favorable pressure structure for surface convergence although the surface environment wind is directing from C_TA toward C_TB.

The vertical structure of perturbation pressure (Fig. 12c) shows that there are two high pressure centers, both located at the cloud base of the two cells, which is also quite different from that with topography (Fig. 6c). The maximum pressure perturbation deviation is only about 0.02 hPa, so the weaker pressure gradient force directed from C_TA to C_TB is formed at the lower levels.

The vertical cross section shown in Fig. 12d along the line CT1DT1 in Fig. 12a suggests that without topography the weak cloud bridge between the two nonprecipitating cells can also be formed (Fig. 12d), which indicates that the formation of upper-level cloud bridge is not produced by the perturbation pressure force directed from one cell to its adjacent cell; instead, it is generated by upper-level outflow of one vigorous cell as discussed above. It is interesting that at 1615 BST the weak cloud bridge is broken though the two independent cells are developed and intensified (Fig. 13). To compare the pressure perturbation distribution at 1545 BST with that at 1615 BST, it can be found that the region between the two cells is fully occupied with a high perturbation pressure center at 1615 BST while at 1545 BST it is a weaker low perturbation pressure (Figs. 12c and 13c); hence, without the topography no persistent pressure gradient force directed from one cell to its adjacent cell is formed. Each cell forms a downdraft because of precipitation process at low levels, and the interactions of the downdrafts induce convergence and a new updraft at the low level between the two cells (Fig. 13c). Thus, the high pressure perturbation center between two cells shown in Fig. 13c is formed because of the upper-level divergence of the new updraft.

To further clarify the mechanisms as to how topography affects the merger process, the vertical distributions of divergence, convergence fields, water vapor mixing ratio, and condensational heating without topography
are presented in Fig. 14, comparing with those in Fig. 8. It indicates that although the convergence field dominates the low levels of cells and the divergence field dominates the mid- and upper levels of the cells at 1545 BST (Fig. 14a), the convergence layer without topography is not as deep and strong as that with topography (Fig. 8a), so it can lead to the lower water vapor content and weaker vapor convergence near the cloud base. With the time evolution of two cells, unlike that with topography, both the divergence and convergence exist at the low levels without topography because of the precipitation-induced downdraft and outflow interactions (Fig. 14b). Thus, without topography, the unfavorable pressure gradient force may not sustain the merging process and lead to the splitting of two initially linked cells.

Therefore, the effect of topography on cloud merging processes is realized by forming a favorable gradient force condition directed from one cell to its adjacent cell under which the stronger convergence field is produced due to the formation of a favorable pressure structure for low-level water vapor convergence and merging processes. The cloud bridge initially formed by upper-level outflow cannot be further enhanced because of the lack of the favorable pressure gradient force and high water vapor convergence under the condition without inclusion of topography.

d. The influence of the large-scale environmental winds on cloud merging processes

The sensitivity test is also performed without initial large-scale environmental winds in the model. The results displayed in Figs. 15 and 16 show that without large-scale environmental winds the initial convection has much weaker intensity. At 1515 BST (Fig. 15a), $C_{WA}$ and $C_{WB}$ have maximum echoes of only 15 and 5 dBZ, respectively. The perturbation pressure field at 4 km shows that $C_{WA}$ is located at the higher perturbation pressure area while $C_{WB}$ is located at the lower perturbation pressure area. The perturbation pressure field at the surface shows that both cells are located at the higher perturbation pressure area (Fig. 15b). A weak cloud

![Figure 15](image-url)
bridge can also be formed between the two cells (Fig. 15c). However, as with the situation without topography, the cloud bridge is broken at 1615 BST (Fig. 16). The perturbation pressure structure is quite similar to that at 1515 BST, but the cloud bridge is broken at this stage.

One of the major differences between simulations with and without large-scale environmental winds is the low-level water vapor convergence area, where a much weaker water vapor convergence field forms, in particular at the area below the cloud bridge when the large-scale environmental winds are not included (Figs. 17a,b).

Both topography and large-scale environmental winds have important effects on the further cloud merging process. The sensitivity tests above suggest that both high low-level convergence induced by topographic lifting and high water vapor in low-level, large-scale environmental airflow have critical roles for the further development and subsequent merging process of isolated cells over the mountainous region in the study.

5. Conclusions and discussion

The cloud merging processes and the effects of mesoscale environmental winds and topography in generating an MCS on 23 August 2001 in the Beijing region were investigated with a cloud-resolving real-case mesoscale simulation of the MM5 model.

The multiscale merging processes play an important role in the formation of the MCS, and the cloud merging processes for the studied case can be classified into three scales: isolated nonprecipitating and precipitating cell merging (with the scale of several to tens of kilometers and one high echo core), cloud-cluster merging (tens to several hundreds of kilometers with several high echo cores), and echo-core or updraft-core merging within cloud systems.

The mechanisms responsible for the merging processes of multiscale clouds were investigated in this study, which shows that the merging processes between nonprecipitating cells, between precipitating cells, and between cloud clusters are initiated by forming an upper-level
cloud bridge between two adjacent clouds due to the upper-level outflow in one vigorous cloud. The cloud bridge is further enhanced by a favorable middle- and upper-level pressure gradient force directed from one cloud to its adjacent cloud by accelerating cloud particles being horizontally transported from the cloud to its adjacent cloud and inducing the redistribution of condensational heating, which can destabilize the air at and below the cloud bridge and forms a favorable low-level pressure structure for water vapor convergence and merging processes.

Further sensitivity studies on the effect of large-scale environmental winds and topography suggest that the stronger low-level water vapor convergence produced by the topographic lifting of large-scale, low-level airflows and favorable pressure gradient force determine the further cloud merging processes over the mountain region. Without the large-scale environmental wind or topography, the cloud bridge initially formed by the upper-level outflow will be broken, and further cloud merging processes cannot be continued.

The multiscale merging processes found in this study are consistent with some previous observational and idealized simulation studies (Simpson et al. 1980; Cunning et al. 1982; Tao and Simpson 1984, 1989). However, some aspects such as formation time of a cloud bridge for the multiscale merging processes are slightly different from previous studies. Our study shows that an upper-level cloud bridge can be formed at the initial and maturing stage of clouds, whereas previous studies indicated that the upper-level cloud bridge for clouds usually occurs in the maturing to dissipating stages (Rotunno et al. 1988; Weisman et al. 1988; Westcott and Kennedy 1989; Westcott 1994; Trier et al. 1997).

The investigation of multiscale merging processes of this study is unique because of the application of a realistic simulation and more emphasis on the effects of large-scale environmental winds and topography, which other more idealized simulations could not resolve. The large-scale environmental wind and topography are found to play critical roles in further cloud merging processes in this study. Without these effects, the cloud bridge formed by upper-level outflow will be broken, and further merging process cannot continue. The favorable pressure gradient force directed from one cloud to its adjacent clouds and high low-level convergence induced by topographic lifting of the large-scale, low-level airflow determine the subsequent merging processes in the mountainous region in this study.

For the merging mechanism of echo cores within the mesoscale convective system, the cold outflow interactions associated with downdrafts of echo cores play an important role, which is also in good agreement with previous studies (e.g., Holle et al. 1977; Simpson et al. 1980; Cunning and DeMaria 1986; Tao and Simpson 1984, 1989; Westcott and Kennedy 1989; Knupp et al. 1998).

Acknowledgments. The authors are grateful for the critical and valuable comments from anonymous reviewers, which greatly improved the quality of this paper. This research has been jointly sponsored by the Chinese Natural Science Foundation (Grants 41005072 and 40575003) and the Key Science & Technology Supporting Project of the Ministry of Science and Technology of China (Grant 2006BAC12B03).

REFERENCES


