A case study of the initiation of parallel convective lines back-building from the south side of a Meiyu front over complex terrain

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Abstract

Parallel back-building convective lines are often observed extending to the southwest of some mesoscale convective systems (MCSs) embedded in the Meiyu front in China. The convective lines with echo training along each of them can quickly develop to be stronger convection group, resulting in local heavy rainfall within the Meiyu front rainband. The initiation mechanism of the back-building convective lines is still unclear and is studied based on high-resolution numerical simulation of a case that occurred during 27-28 June 2013. In the present case, the new convection along the convective lines are found to be forced by nonuniform interaction between the cold outflow associated with the Meiyu front MCSs and the warm southerly airflow on the south side of the Meiyu front, which both are modified by local terrain. The Meiyu front MCSs evolved from the western to the eastern of a basin surrounded by several mesoscale mountains and induced cold outflow centered over the eastern of the basin. The strong southwest airflow ahead of the Meiyu front passed through the Nanling Mountains and impacted upon the cold outflow within the basin. The nonuniform interaction led to the first stage of parallel convective line formation, in which the low mountains along the boundary of the two airflows enhance the heterogeneity of their interaction. Subsequently, the convection group quickly developed from the first stage convective lines resulted in evident precipitation cooling that enhanced the cold outflow and made the cold outflow a sharp southward shift. The enhanced cold outflow pushed the warm southerly airflow southward and impacted upon the mountains on the southeast side of the basin, where the roughly parallel mountain valleys or gap paly a control role in a second stage formation of parallel convective lines.

Keywords: back-building convective line, convective initiation, complex terrain, Meiyu front

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Article Highlights:

- Evolution of the Meiyu front MCSs over a basin induces cold outflow centered over the eastern part of the basin.
- The low mountains within the basin modify the cold-warm airflow interaction resulting in the first stage formation of the convective lines.
- The mountains on the southeast side of the basin play a control role in the second stage formation of the convective lines.
1. Introduction

Mesoscale convective systems (MCSs) are often observed accompanying back-building convective lines which support their organization and maintenance for a long time and induce heavy precipitation (Ding et al., 2018; Duffourg et al., 2016; Huang et al., 2019; Lee et al., 2018; Luo et al., 2013; Schumacher and Johnson, 2005; Tsuguti et al., 2019; Wang et al., 2014). The back-building process consists of the periodic appearance of new cell upstream merging with the preexisting line of convection (Bluestein et al., 1987; Bluestein and Jain, 1985) or “echo training” of convective cells, and is primarily due to the interaction between the MCS cold outflow and the surrounding airflow.

The characteristics of the MCSs and the associated back-building convective lines are different in different synoptic environments. The back-building MCSs east of the Rocky Mountains in the United States have a quasi-stratiform area of convection that produces a region of stratiform rain downstream, and the back-building process generally dependent on lifting provided by storm-generated cold pools (Schumacher and Johnson, 2005). Over the northwestern Mediterranean, back-building quasi-stationary MCSs often form in an environment of moist and conditionally unstable air, which is carried by a southwesterly to southeasterly low-level marine flow (Ducrocq et al., 2013). The low-level cold pool under the MCS can lift the marine flow (Ducrocq et al., 2008) or modify the low-level circulation to enhance convergence forcing locally (Duffourg et al., 2016) to induce back-building processes. When this moist and
conditionally unstable flow impinges on some of the mountains along the western Mediterranean, orographic lifting has been proposed as a mechanism for triggering heavy precipitation events involving back-building MCSs (Buzzi et al., 1998; Ducrocq et al., 2008; Rotunno and Ferretti, 2001).

In east China, the MCSs associated with a quasi-stationary or slow-moving front during the Meiyu season (also known as the Changma season in Korea or the Baiyu season in Japan) are essential systems to produce heavy rainfall events over the Yangtze-Huai Rivers basin (Chen et al., 1998; Ding, 1992; Luo et al., 2013; Zhang and Tan, 2009). Some MCSs embedded with line-shape back-building convection are often observed along the Meiyu front. Luo et al. (2013) investigated a back-building MCS along a Meiyu front during the midnight-to-morning hours and found two scales of the convective organization during the development of the MCS: one is the east- to northeastward “echo training” of convective cells along individual rainbands, and the other is the southeastward “band training” of the rainbands along the quasi-linear MCS. MCSs with a similar convective organization as in Luo et al. (2013) are also found in extreme rainfall events occurred over coastal South China during the presummer rainy season (e.g., Liu et al., 2018; Wang et al., 2014), while the mesoscale mountains near the coastal line sometimes can play a role in the convective initiation and organization.

The back-building MCS in Luo et al. (2013) occurred in an area of flat terrain, while a lot of mountains with a mean height of ~ 1000 m can be found over the Yangtze-Huai Rivers basin (Wang and Tan, 2006), and could take effect on the back-building MCSs
along the Meiyu front. Sun (2015) found the mountains favor the formation and maintenance of the back-building pattern of a Meiyu front MCS, but the role of the mountains was not revealed in detail. For the Meiyu front MCS over complex terrain, it is still not clear how the mountains modify the cold outflow under the MCS and how the mountains alter the back-building process of the convective lines associated with the MCS. Moreover, the mountains on the south side of the Meiyu front can modify the upstream airflow that approaches the Meiyu front and then can affect the evolution of the back-building MCS. This study will investigate a typical case involving back-building MCSs over complex terrain during the Meiyu season, and the aim focuses on the role of the complex terrain in the formation of the back-building convective lines associated with the Meiyu front MCSs.

The rest of this paper is organized as follows: Section 2 gives an overview of the case. The numerical model and experiment design for the simulation of the case are introduced in section 3. The results are discussed in detail in section 4. Finally, a summary is given in section 5, including a conceptual model of the role of the complex terrain in the formation of the back-building convective lines.

2. Overview of the case

This case took place over a basin area in Jiangxi Province of China, which is surrounded by the mountains Wuyi, Yu, Wugong, Jiuling and Mufu, Dabie, and Huang (Figure 1a). The basin area is enlarged in Figure 1b, and an important gap between the
mountains Yu and Wuyi is denoted with an arrow. Focused are two stages of convective line formation, and the associated back-building processes occurred primarily within two zones, which are denoted as two dashed rectangles in Figure 1b, respectively.

The NCEP 0.25°×0.25° reanalysis data (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce et al., 2003) are used to reproduce the weather background of the case. At 1800 UTC 27, or 0200 LST 28, June 2013 (Figure 1c), the Meiyu front region with weaker temperature gradients and low wind speeds covered the basin area. The leading edge of the Meiyu front, identified by the sharp contrast of the near-surface horizontal wind vectors at 10 m above ground level along the south boundary of the weaker gradients of 2-m temperature, was located on the north side of the mountains Nanling and Wuyi. To the west of the basin, there was a low embedded within the Meiyu front. The circulation of the low showed interactions with the southerly airflow ahead of the Meiyu front and also with the Mountains Jiuling and Mufu, where two cloud clusters labeled with A and B formed. The cloud clusters in Figure 1 are outlined with -40 °C of the infrared brightness temperature (TBB) retrieved from Multi-functional Transport Satellite (MTSAT) (the data are obtained from the satellite data archive for research and education at http://weather.is.kochi-u.ac.jp/sat/GAME/).

In the next 6 hours, the cloud cluster B moved eastward and quickly developed within the basin area (Figure 1d). The cloud cluster A also got developed and had moved over the mountains Jiuling and Mufu. The southerly airflow ahead of the Meiyu
front became stronger at this time, and both the two cloud clusters extended southwestward to the first back-building zone, showing more or less back-building features. The back-building feathers are supposed to be a result of interaction between the stronger southerly airflow and the cold outflow associated with the precipitation of the two cloud clusters.

Six hours later (Figure 1e), the cloud cluster B weakened and moved out of the basin area, the cloud cluster A also weakened and separated to be lines of cloud cluster. To the southwest of the cloud cluster A, a new cloud cluster C formed, which also shown a back-building feature on its southwest side within the first back-building zone. The cloud clusters C and A exhibited line shape that roughly parallel to each other, and their back-building development pushed the leading edge of the Meiyu front southward evidently.

Another 6 hours later (Figure 1f), the cloud clusters C and A also moved out of the basin area and dissipated. While a new cloud cluster D covering the second back-building zone, which originated roughly from where C quickly grew, and a new cluster E east to D developed rapidly along the mountains Yu and Wuyi, and further pushed the leading edge of the Meiyu front southward.

The detailed evolution of the cloud clusters mentioned above is shown in Figure 2 in hourly maps. Note the line features of the cloud clusters A and C in Figure 2d, which can be identified from the lower values of TBB and the wave pattern of the south sides of the two cloud clusters. This is the first stage (stage I) of back-building starting from
the first back-building zone shown in Figure 1b. The development of cloud cluster D also shows line features of back-building (Figure 2j), and the back-building development of the cloud cluster E east to D is much clearer (Figure 2h-j). The second stage (stage II) of back-building starts from the second back-building zone shown in Figure 1b and is also associated with the interaction between the cold outflow in the basin area and the southerly airflow ahead of the Meiyu front. At the same time, the mountains on the way should play an important role as the leading edge of the Meiyu front moved southward.

3. Numerical model and experiment design

Version 5 of the Advanced Regional Prediction System (ARPS, Xue et al., 2000, 2001; Xue et al., 2003), a non-hydrostatic atmospheric model, is used to perform the simulations of the case. The model domain has $651 \times 579$ horizontal grid points with a 1-km grid spacing, which is nested in a 3-km grid of $483 \times 403$ horizontal grid points (Figure 3). A generalized terrain-following coordinate is used in vertical, and 53 stretched levels are defined with the grid spacing increasing from about 20 m near the ground to about 800 m near the model top at about 20 km. The model terrain and land surface characteristics on the 3- and 1-km grids are derived from the 30-arc seconds (approximately 1 kilometer) global elevation and landuse data set from the U.S. Geological Survey.
The model is initiated at 1200 UTC 27 June 2013 and is integrated for 36 hours until 0000 UTC 29 June 2013. For the 3-km grid, the lateral boundary conditions (LBCs) are generated from GFS global 0.5-degree analysis fields at 6-hour intervals obtained from the Historical Unidata Internet Data Distribution (IDD) Gridded Model Data (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce et al., 2003). The initial condition for the 3-km grid is created using the ARPS three-dimensional variational (3DVAR) data analysis scheme (Gao et al., 2004) based on the GFS global 0.5-degree analysis fields and the conventional radiosonde and surface observations shown in Figure 3. The nested 1-km grid gets its initial condition from the interpolation of the 3-km analysis and its LBCs from the 3-km forecasts at 10-min intervals. The ARPS is used in its full physics mode, as in Wang and Xue (2012).

In this case, the cold outflow is generally confined within the basin surrounded by the mountains Mufu-Jiuling and Huang on the north side, and several low mountains are scattered among the first back-building zone where stage I convective lines formed. It is not clear whether the low mountains play a role in the formation of stage I convective lines. Either, it is not clear whether the mountains Mufu-Jiuling and Huang play a role in altering the strength of the cold outflow within the basin and, thus, the back-building processes associated with the cold outflow interacting with the southerly along the front leading edge during the two stages of convective line formation. To understand the two points in doubt, sensitive experiments with the mountains parallelly
near the leading edge of stage I convective lines removed (NoMidMts) and with the mountains Mufu-Jiuling and Huang on the north side of the basin removed (NoNorthMts) are designed respectively (Table 1).

4. Results

4.1 The simulated convective lines and cold outflow

Figure 4 shows the observed (left, obtained from radar observations at Nanchang, Jian, and Shangrao as shown in Figure 3) and the simulated (right) composite radar reflectivity (RFC) at 0300 and 0900 UTC 28 June 2013. The lines of the cloud cluster in Figure 2d and 2j primarily correspond to the lines of RFC shown as dashed lines in Figure 4a and 4c, respectively. The line features of the RFC at the two stages are generally reproduced in the simulation (dashed lines in Figures 4b and 4d), except the simulated RFC is slightly larger, and the position of the convective lines is slight to the south of the observed convective lines. The simulation also reproduces the broad stratiform region that follows the convective lines at the two stages (Figure 4a-b and 4c-d). The convective line corresponding to the cloud cluster E in Figure 2j was initiated later in the simulation and did not separate from the other convective lines (Figure 4d), as observed (Figure 4c), which will be discussed next.

The two stages of back-building convective line formation are associated with the interaction between the cold outflow in the basin and the southerly airflow ahead of the Meiyu front, as discussed in section 2. The cold outflow linking with precipitation in
the basin is shown in Figure 5. The precipitation data used in Figures 5a and 5b is the 
hourly, 0.1° × 0.1°, gauge-satellite merged precipitation product, which can be obtained 
from the National Meteorological Information Center of China (available at 
http://data.cma.cn/data/detail/dataCode/SEVP_CLI_CHN_MERGE_CMP_PRE_HO 
UR_GRID_0.10/keywords/CMORPH.html). The station temperature in Figures 5c and 
5d is from the observations of the automatic weather stations (AWS).

The centers of accumulated precipitation from 0000 UTC 27 to 0300 UTC 28 June 
2013 are mainly over the mountains Jiuling and the western of the basin between the 
mountains Wuyi and Huang (Figure 5a), roughly corresponding to the centers of cold 
outflow when stage I convective lines formed (Figure 5c). The development of stage I 
convective lines induced heavy precipitation in the next 6 hours, and the accumulated 
precipitation by 0900 UTC 28 June 2013 becomes larger, spreading southward and 
extending to the southwestern of the basin between the mountains Wugong and Yu 
(Figure 5b). The cold outflow centers less match the centers of the accumulated 
precipitation (Figure 5b and 5d) due to the cold outflow that responded more directly 
to the recent 6-hour precipitation. The cold outflow moved towards the mountains Yu 
and Wuyi and pushed the leading edge of the Meiyu front (stronger gradient of 
temperature) southeastward evidently within the 6 hours (Figure 5c and 5d). It is 
suggested that the mountains Yu and Wuyi would modify the interaction between the 
cold outflow and warm southerly airflow along the leading edge of the Meiyu front, 
which should connect with the formation of stage II back-building convective lines.
The simulated cold outflow in the basin is weaker than the observations (Figure 5c-d and 5e-f), while the cold outflow centers over the western of the basin between the mountains Wuyi and Huang (Figure 5e) and their approaching to the mountains Yu and Wuyi (Figure 5f) are generally captured in the simulation. The simulated weaker cold outflow is partially associated with initial errors and model uncertainties, which starts at 1200 UTC 27 June 2013 and cannot produce long-time accumulated precipitation, as in Figure 5a, b. While if the simulation begins earlier, the prediction of the convective line formation will not be as good due to the uncertainty associated with the initiation and evolution of the convection in the model (not shown).

The warm southerly airflow near the surface is also weakly simulated in terms of temperature (Figure 5c-d and 5e-f). At 0300 UTC 28 June 2013, the simulated boundary of the warm southerly airflow is fuzzy near the surface (Figure 5e). This should be partially associated with the unperfect representation of the mountain and valley circulations to the lee side of the mountains Nanling due to shorter integration of the model. By 0900 UTC, the simulated near-surface boundary of the southerly airflow becomes clear and primarily consistent with that of the observations (Figure 5d and Figure 5f). While the border differs locally near the gap between the mountains Yu and Wuyi, it is the cold outflow that intrudes into the gap in the simulation instead of the warm southerly airflow in the observations (Figure 5f and Figure 5d). The cold outflow intrusion into the gap in the simulation results in a later formation of the convective line than that in the observations (the right convective line in Figure 4c and Figure 4d).
Note that the orientation of the stratiform region in Figure 4 is roughly west-eastward at 0300, but changes to be about southwest-northeastward at 0900 UTC 28 June 2013. Figure 2 suggests that the stratiform region partially comes from the decaying of the former convection groups along the Meiyu front. When new convective regions generate on the south side of the stratiform region, processes associated with the detrainment of air from the convective regions and the transition of the weakening convective regions to stratiform regions should play an important role as discussed in Luo et al. (2010). Figure 6 shows the soundings at Nanchang within the stratiform region at two times. A mid-level westerly exists between 700 and 500 hPa (Figure 6), and the mean wind direction between the two levels primarily indicates the orientation of the stratiform region at the two times, respectively. Generally, the orientation of the stratiform region is directly linked with mid-level flow associated with the front that blows them away. The motion of the convective lines shows a similar orientation as that of the stratiform region due to the blow of the mid-level flow, while the orientation of the convective lines or cell motion closely follows the direction of the southwest flow that impinges on the Meiyu front.

Below 900 hPa, the southeast winds dominate (Figure 6), indicating that the cold air flows from the cold outflow center to the sounding location at Nanchang. As the leading edge of the front advanced southward between 0300 to 0900 UTC 28 June 2013, the main body of the stratiform region gradually deviated from Nanchang, leaving a drier and slightly warmer air in the mid-and-lower levels at Nanchang. But the near-
surface cold airflows from the cold outflow center can still reach Nanchang, making
the near-surface air at 0900 colder than that at 0300 (Figure 6).

Overall, the convective lines, the cold outflow within the basin, and the warm
southerly airflow ahead of the Meiyu front are reasonably simulated with identifiable
correspondence to the observations, despite differences in strength and position details.
This establishes the credibility of the model simulation to be further analyzed with a
certain degree of confidence in the next sections.

4.2 Formation of convective lines during stage I

Low-level horizontal cross-sections through the constant height of 250 m and 500
m mean sea level (MSL) are plotted in Figure 7 for the formation of stage I convective
lines. The cross-sections clearly show the interaction between the cold outflow and the
warm southerly airflow and their modification by the local mountains. The convective
lines along A1B1-A5B5 in Figure 7c-f correspond to those shown as dashed lines in
Figure 4b.

Within half an hour before the line features of the convection group are apparent
(Figure 7a-d), the cold outflow centers at 250 m and 500 m MSL are over the western
of the basin, and between the mountains Wuyi and Huang as those near the surface
(Figure 5e). The boundary between the cold outflow and the warm southerly airflow at
250 m MSL is primarily consistent with that near the surface (Figure 7c and Figure 5e)
and is in a quasi-steady state (Figure 7a and Figure 7c). Within the basin, the airflow at
250 m MSL is generally colder than that near the surface because of the temperature lapse rate and less accumulated precipitation and cooling near the surface due to a shorter integration of the model.

At 0230 (Figure 7a), the warm southerly airflow passes through the mountains Nanling, Wugong, and Yu and converges with the cold outflow roughly along a line from the mountains Jiuling to the north of the mountains Yu (AB in Figure 7c-f). At 500 m MSL (Figure 7b), the airflow pattern is similar, while the southerly airflow is stronger than that on 250 m MSL, resulting in clearer convergence forcing where it meets the cold outflow. The strongest convergence forcing is found to the downstream of the mountains Wugong on both of the two levels due to strong lee side convergence (Figure 7a-b).

The airflows on the two levels keep a quasi-steady pattern in the next half an hour (Figure 7c-d), except that the southerly airflow gets slightly warmer and stronger. The stronger southerly airflow induces apparent convergence forcing to the downstream of the mountains Wugong, which supports the maintenance of convection along A1B1 on the warm air side. The convection along A1B1 on the cold air side shows some features of back-building (Figure 7c and Figure 7e). On the warm air side, another two formerly formed convection pieces are advected toward and tend to merge with the cold air side convection group where more or less back-building features appear. This makes the convection group taking a line shape along A2B2 and A3B3 (Figure 7c and Figure 7e).
While the convective lines A4B4 and A5B5 extend southwestward from the convection group, showing back-building features clearly (Figure 7c and Figure 7e).

It is easy to understand that the west part of the convection group shifts to the south of the cold-warm airflow boundary due to the convection formed on the warm air side. Back-building is generally associated with cold-warm airflow interaction along its boundary. In this case, the interaction between the cold and warm airflow is ununiform. It could be modified by the local mountains, as shown in the vertical cross-section roughly along their boundary (Figure 8a). Also, the interaction should be affected by the convection on the warm air side. The detailed interaction and the associated back-building processes are shown in vertical cross-sections through the convective lines A1B1-A5B5 in Figure 8b-f, respectively.

In the vertical cross-section along AB in Figure 7c (Figure 8a), five updraft bunches can be identified where the convective lines A1B1-A5B5 intersect with AB. The warm (cold) air tends to be thicker on the left (right) side of each of the terrain profile along AB, indicating modification of the cold-warm airflow interaction by the local terrain. Along each of the five convective lines (Figure 8b-f), successive updrafts are found along a slant over the cold air side, which is associated with the general structure of the Meiyu front. New updraft feeding the Meiyu front updrafts continuously generates near the cold-warm airflow boundary at a low level, clearly demonstrating a back-building structure.
Upstream of the slant-along updrafts along the convective line A1B1 (Figure 8b), convection forced by the convergence to the lee side of the mountains Wugong (see Figure 7c-f) produces evident downdraft, which enhances the low-level convergence that contributes to the formation of the back-building new updraft. Along the convective line A2B2 (Figure 8c), upstream convection is induced by low mountains, which is weak and takes no obvious effects on the downstream back-building new updraft. In contrast, the upstream convection along the convective line A3B3 (Figure 8d) is strongly induced by higher mountains. It can produce downdraft that strengthens the low-level convergence supporting the formation of the back-building new updraft as that along the convective line A1B1. The back-building features along the convective lines A4B4 (Figure 8e) and A5B5 (Figure 8f) are clearer since there is no upstream convection. For some of the convective lines encountering the mountains near the cold-warm airflow boundary, the local mountains play a role in the formation of the back-building new updraft, e.g., through upstream lifting (e.g., Figure 8d, f) or lee side downslope wind convergence (Figure 8f).

4.3 Formation of convective lines during stage II

The processes associated with the formation of the convective lines during stage II are shown in Figure 9. The development of the convective lines of stage I results in evident precipitation cooling and the centers of the cold outflow have moved to the southeastern of the basin along the mountains Yu and Wuyi by 0830 UTC 28 June 2013.
(Figure 9a, b). Note the gap between the mountains Yu and Wuyi and the valleys among the mountain branches on the northwest side of the mountains Yu. The cold outflow first runs into the gap and the valleys, and strong convergence between the cold outflow and the warm southerly airflow is found along the leading edge, which is more clearly shown on 500 m MSL (Figure 9b). The boundary of convergence is followed by several back-building convective lines, indicating that the forcing for back-building comes from the cold-warm airflow interaction associated with terrain modification at a low-level.

The airflows described above keep a similar interaction pattern in the next half an hour (Figure 9c-d). During this period, the cold outflow intrusion is quick and strong and results in a stage of clearer back-building at 0900 UTC (Figure 9c and Figure 9d). The convection group extends southwestward roughly along line CD over the mountains Yu. Along the line, the convergence boundary shows a clear wave pattern (Figure 9f), denoting evident modification by the local terrain. Five convective lines are primarily identified. The convective line C1D1 is along the mountains Yu and gets to the lee side of the mountains Nanling. The convective lines C2D2-C4D4 are roughly along the major valleys on the northwest side of the mountains Yu, and the convective line C5D5 primarily follows the gap between the mountains Yu and Wuyi. Vertical cross-sections along these lines are shown in Figure 10 to illustrate the processes resulting in the forcing that supports the back-building.
Warm air alternating with cold air along the line CD show ununiform interaction between the warm southerly airflow and the cold outflow (Figure 10a), and the associated updrafts can be found roughly where the horizontal gradient of temperature is higher. The updrafts corresponding to the selected convective lines C2D2-C5D5 are near where they intersect with the line CD (Figure 9c and Figure 9d). For the convective line C1D1 that extends to the lee side of the mountains Nanling (Figure 10b), the airflow interaction at a low level and the associated convergence forcing are not strong due to mountain shading. Instead of surface-based, the new updraft is due to the interaction between the mid-level (3-5 km MSL) stronger southerly airflow and the leading convection (Figure 10b). The back-building new updrafts for convective lines C2D2-C5D5 are all surface-based (Figure 10c-f), but the sources of forcing are different in detail depending on the cold-warm airflow boundary related to the topography. When the cold outflow has not reached the mountain top (e.g., Figure 10d), the cold-warm airflow convergence provides the forcing for back-building on the near-basin side of the mountain, and the existing convection can get support from the lifting of the cold outflow by the mountain. As the cold outflow just surmounts the mountain top (e.g., Figure 10c), the leading updraft is associated with the convergence between the warm air and a thin near-surface layer of cold downslope outflow and the lifting of the warm southerly airflow by the mountain above. When the leading convection passes the top of the mountain (e.g., Figure 10e), the mountain downslope can enhance the cold outflow associated with the downdraft of the convection, which will strengthen the
cold-warm airflow interaction, and thus the leading updraft. Along the gap between the mountains Yu and Wuyi (Figure 10f), the processes are similar to that along convective line C4D4 (Figure 10e), except the topographic effects can be neglected since the terrain along the gap is much lower.

4.4 The role of the mountains within and surrounding the basin

For the formation of the convective lines during stage I, the low mountains along the leading edge of the cold outflow are within the basin. They are discontinuous (Figure 7c and Figure 8a), the importance of these low mountains is not clear since some studies show that back-building convective lines can form in a condition of plain terrain (e.g., Luo et al., 2013). For the convective line formation of stage II, the mountains ahead of the cold outflow are on the southeast side of the basin and are continuous (Figure 9c and Figure 10a). The mountains play an important role, as discussed in section 4.3. The experiment NoMidMts investigates the role of the low mountains within the basin in the formation of stage I convective lines, and the experiment NoNorthMts will examine the role of the mountains on the north side of the basin that probably changes the strength of cold outflow and subsequently the back-building processes.

As the control experiment (CNTL), both of the two experiments are initiated at 1200 UTC 27 June 2013 and are integrated until 0000 UTC 29 June 2013. The modified terrain for each of the two experiments is smoothed to avoid integration instability.
associated with terrain removal that could result in a very sharp terrain profile. The
smoothed terrains for the two experiments primarily keep characteristics of the terrain
in the experiment CNTL where they are not modified (Figure 11 and Figure 12), and
the modified terrain will alter the processes of the convective line formation associated
with different terrain conditions.

In the experiment NoMidMts (Figure 11), the convection group shows line features.
Still, the convective line number decreases since the interaction between the cold
outflow and the warm southerly airflow becomes less ununiform without being
disturbed by the low mountains (Figure 11a, b). In the absence of the mountains
Wugong and the enhanced convergence forcing on its lee side, the convection group is
primarily along the cold-warm airflow boundary instead of shifting its west part to the
warm side of the boundary as in the experiment CNTL (Figure 11a and Figure 7c).
Some parts of the mountains Yu and Wuyi are also removed in the experiment
NoMidMts. This makes the cold outflow spreads toward the mountains Yu and Wuyi
more quickly than that in the experiment CNTL (Figure 11c-d and Figure 9c-d).
The experiment NoNorthMts shows that the cold outflow over the original basin
area becomes broader (Figure 12), merging with the cold air that should be between the
north side of the Meiyu front and the mountains Mufu-Jiuling and Huang in the
experiment CNTL (Figure 1b). The merger more or less enhances the cold outflow over
the basin area, whose low-level leading edge by 0300 UTC 28 June 2013 is roughly at
y = 300 km (Figure 12a-b) that is south to the leading edge of the cold outflow in the
experiment CNTL (Figure 7c-f). The convection group in the experiment NoNorthMts forms and develops further southward and later results in a quicker advance of the cold outflow into the mountains Yu and Wuyi than that in the experiment CNTL (Figure 12c-d and Figure 9c-d).

To illustrate the terrain effects on the low-level forcing that contribute to the formation of the convective lines during stage I, the time evolution of key relevant fields along AB in Figure 7c on 250 m MSL is compared between the experiment CNTL and the experiments NoMidMts and NoNorthMts in Figure 13. In the experiment CNTL (Figure 13a, b), more low-level convergence bands (slash-filled blue contours in Figure 13a) coupling with lifting forcing (slash-filled blue contours in Figure 13b) form due to ununiform cold-warm airflow interaction. The terrain around x = 100 km induces evident warm airflow convergence on the left side and cold outflow convergence on the right side. This results in convergence forcing supporting the development and maintenance of two of the convective lines (dash-filled red contours in Figure 13a, b) later. The right shifting of the convective lines with time clearly shows an eastward “band training” organization of the convective lines, as summarized in Luo et al. (2013).

In the experiment NoMidMts (Figure 13c, d), bands of convergence forcing cannot form around x = 100 km where the terrain is removed, and the adjacent convective lines are more intermittent instead of continuous. The cold outflow becomes stronger in the experiment NoNorthMts (Figure 13e, f), it is clear that the terrain along AB in Figure 7c still helps to maintain warm airflow convergence on its left side and cold outflow
convergence lifting on its right side. This confirms that the low mountains along the cold-warm airflow boundary increase the non-uniformness of the cold-warm airflow interaction by inducing long-lasting low-level convergence forcing that favors the formation of back-building convective lines.

As in Figure 13, the time evolution of the same fields along CD in Figure 9d on 500 m MSL is shown in Figure 14 to illustrate the low-level forcing associated with terrain effects that contribute to the formation of the convective lines during stage II. In the experiment CNTL (Figure 14a, b), the convergence lifting forcing starts when the cold outflow meets the warm southerly airflow. The wavy boundary of cold-warm airflow interaction is primarily controlled by the mountain tops and valleys along CD (Figure 10a). Several convective lines originate from some of the convergence forcing, and their maintenance along CD indicates continuous back-building that supports the formation of some of the convective lines shown in Figure 9c-d. Note not all the convective lines in Figure 9c-d have corresponding RFC field in Figure 14a-b because the line CD is roughly through the cold-warm airflow boundary instead of crossing the leading parts of all the convective lines. As the organization of the convective lines during stage I, the northeastward “band training” along CD is clear during this stage. Similar features exist in the experiments NoMidMts (Figure 14c, d) and NoNorthMts (Figure 14e, f). However, the cold-warm airflow interaction near the line CD occurs about 1 hour earlier due to quicker development of the stronger cold outflow in the two
experiments, as discussed above. The terrain plays a control role in the convective line formation during stage II.

5. Summary and conclusions

The formation of parallel convective lines along the south side of the Meiyu front during 28 June 2013 in China is studied through numerical simulations at 1 km horizontal grid spacing using a mesoscale numerical model. Two stages of convective line formation observed with back-building features are reasonably simulated.

The two stages of convective line formation are associated with the interaction between the warm southerly airflow ahead of the Meiyu front and the cold outflow induced by the Meiyu front mesoscale convective systems (MCSs) evolving over a basin surrounded by the mountains Wuyi, Yu, Wugong, Jiuling and Mufu, Dabie, and Huang. The low mountains within the basin and the mountains on the southeast side of the basin play important roles during the two stages of convective line formation, respectively, which is summarized in a conceptual model, as illustrated in Figure 15.

During stage I (Figure 15a), the warm southerly airflow passes the mountains Nanling, Wugong, and Yu and meets the cold outflow within the basin. A convection region starts from the cold-warm air boundary (or the leading edge of the Meiyu front). It is followed by a main stratiform region within a broad cloud sector covering the basin. The cold outflow within the basin is primarily due to precipitation cooling associated with MCSs that propagated along the Meiyu front from the mountains Mufu-Jiuling
while were prevented by the mountains Wuyi and Huang on the east side of the basin earlier. The cold outflow center is between the mountains Wuyi and Huang, where the accumulated precipitation is larger. The low-level cold outflow spreads from the cold outflow center and interacts with the warm southerly airflow nonuniformly along the leading edge of the Meiyu front. The low mountains along the leading edge of the Meiyu front can increase the non-uniformness of the interaction. Back-building processes continuously occur where the interaction is stronger along the quasi-steady leading edge of the Meiyu front and supports the formation and maintenance of the convective lines. Also, low-level convergence forcing due to interaction between the mountains and the warm southerly airflow induces several convective pieces ahead of the Meiyu front, especially the convergence forcing to the lee side of the mountains Wugong. The convective pieces are found in line with and approaching some of the convective lines. The associated downdrafts can play a role in enhancing the back-building processes near the leading edge of the Meiyu front. For each of the convective lines, the cell motion is along the convective line. In contrast, the motion of the convective lines is primarily consistent with the mid-level west-eastward flow associated with the front.

The development and eastward propagation of the convective lines formed during stage I result in new precipitation cooling that strengthens the cold outflow. The cold outflow center becomes broad and extends southwestward along the southeast side of the basin, resulting in a sharp southwest shift of the convection region, the stratiform
region, and the cloud sector (Figure 15b). The strong cold outflow intrudes into the
valleys on the northwest side of the mountains Yu and the gap between the mountains
Yu and Wuyi and pushes the warm airflow southward. Convective lines form along the
main valleys and the gap, with the convective line along the gap being stronger since
the gap is broader than the valleys, and the intrusion of the cold outflow into the gap is
more intense. The gap plays a role in accelerating the cold outflow and thus to enhance
its interaction with the warm southerly airflow. The valleys can induce additional
forcing through confluence and uplifting or downslope flow to enhance the cold-warm
airflow interaction. These result in a control role of the terrain in the formation of the
convective lines during stage II. During this stage, the cell motion is also along each of
the convective lines, and the motion of the convective lines is still primarily consistent
with the mid-level flow associated with the front, which has changed to be southwest-
northeastward.

This conceptual model contains a broad stratiform region and is different from the
schematic diagram of the quasi-linear-shaped MCS in Luo et al. (2013), in which the
stratiform rainfall is little. The conceptual model appears to be similar to that of the
MCS climatology with training line and adjoining stratiform in North America
(Schumacher and Johnson, 2005) in terms of the stratiform region, but differs in the
formation of the convective lines and the motion of the echo training. The echo training
along the convective lines is similar to that of the back-building MCS in Schumacher
and Johnson (2005) and Luo et al. (2013). More importantly, the mountains play
significant roles in the conceptual model. Sensitivity experiments confirm the
modification role of the low mountains within the basin during stage I and the control
role of the mountains Yu and Wuyi on the southeast side of the basin during stage II of
the convective line formation. Knowledge of the effects of the mountains on the
convective line formation is helpful for the understanding and prediction of heavy
precipitation events over the basin region during the Meiyu season in China.

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The NCEP reanalysis data used to reproduce the weather background and to initialize
the simulations were downloaded from the NCAR Data Archive. The infrared
brightness temperature data used to show the cloud clusters were obtained from the
satellite data archive for research and education at http://weather.is.kochi-
u.ac.jp/sat/GAME/. The observed precipitation data were obtained from the National
Meteorological Information Center of China (available at
http://data.cma.cn/data/detail/dataCode/SEVP_CLI_CHN_MERGE_CMP_PRE_HO
UR_GRID_0.10/keywords/CMORPH.html). The observed station temperature data
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References


Table 1. Experiment design.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CNTL</td>
<td>The control experiment using real terrain.</td>
</tr>
<tr>
<td>NoMidMts</td>
<td>The mountains parallelly near the leading edge of stage I convective lines are removed.</td>
</tr>
<tr>
<td>NoNorthMts</td>
<td>The mountains Mufu-Jiuling and Huang on the north side of the basin are removed.</td>
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</tbody>
</table>
Figure 1. Panels (a) and (b) show the terrain features. The terrain height is shaded in grayscale. A basin and surrounded mountains of Nanling, Wugong, Yu, Wuyi, Jiuling, Mufu, Dabie, and Huang are denoted in (a). The basin area outlined with a solid box in (a) is enlarged in (b) with two zones of back-building and the gap between mountains Yu and Wuyi denoted. Panels (c-f) show the mean sea level pressure (blue contours, hPa), 2-m temperature (red contours, °C), 10-m horizontal winds (vectors, m s⁻¹), and the infrared brightness temperature (TBB) at -40 °C (thick blue contours) at (a) 1800 UTC 27 June 2013, (b) 0000, (c) 0600, and (d) 1200 UTC 28 June 2013. The fields of pressure, temperature, and wind are plotted from the NCEP 0.25°×0.25° reanalysis data. The TBB data are obtained from the satellite data archive for research and education at http://weather.is.kochi-u.ac.jp/sat/GAME/. The evolution of two focused cloud clusters (labeled with “A” and “B”) in the dashed box region in (c) is shown in Figure 2. The bold dashed line denotes the south leading edge of the Meiyu front. The first zone and the second zone of back-building are also shown in (d-e) and (e-f), respectively. See the text for the details.
Figure 2. Evolution of TBB (shaded) in the dashed box region in Figure 1a at (a) 0000, (b) 0100, (c) 0200, (d) 0300, (e) 0400, (f) 0500, (g) 0600, (h) 0700, (i) 0800, and (j) 0900 UTC 28 June 2013. The focused cloud clusters are labeled as A, B, C, D, and E. The black dashed lines denote the positions of the cloud clusters. The red dashed lines in (d) and (j) show the line features of the cloud clusters. The TBB data are obtained from the satellite data archive for research and education at http://weather.is.kochi-u.ac.jp/sat/GAME/.
Figure 3. The 3-km model domain nested with a 1-km subdomain (solid box). The small triangles and circles mark the stations from conventional radiosonde and surface networks, respectively. The small squares mark radar locations of Nanchang (NC), Jian (JA), and Shangrao (SR), with large circles indicating their maximum radar ranges. The dashed box denotes the horizontal plotting region in later figures. The terrain elevation is shaded in grayscale with mountainous regions denoted as in Figure 1a.
Figure 4. Observed (left) and simulated (right) composite radar reflectivity at (a, b) 0300 and (c, d) 0900 UTC 28 June 2013. The dashed lines denote the line features of the composite radar reflectivity.
Figure 5. Accumulated precipitation from 0000 UTC 27 to (a) 0300 and (b) 0900 UTC 28 June 2013, and observed near-surface temperature at (c) 0300 and (d) 0900 UTC 28 June 2013. The plots of simulated near-surface temperature at 0300 and 0900 UTC 28 June 2013 are shown in (e) and (f), respectively. The red star in (a) denotes the location of Nanchang (NC), where the soundings are extracted from model forecasts and are shown in Figure 6. The observed precipitation data are from the gauge-satellite merged precipitation data obtained from the National Meteorological Information Center of China (available at http://data.cma.cn/data/detail/dataCode/SEVP_CL_1_CHN_MERGE_CMP_PRE_HO UR_GRID_0.10/keywords/CMORPH.html). The observed temperature data were from the observations of the automatic weather stations (AWS) shown as dots in (c).
Figure 6. Skew-T plots of soundings extracted from the model simulation at the red star in Figure 5a, at 0300 (red), and 0900 (blue) UTC 28 June 2013.
Figure 7. Temperature (shaded, °C), wind vectors, and convergence (blue contours, with an interval of $2 \times 10^{-3}$ s$^{-1}$) at (left) 250 m and (right) 500 m MSL, with the times at (a, b) 0230 and (c, d) 0300 UTC 28 June 2013. The red contours show the 45 dBZ composite radar reflectivity at the corresponding times. The lines in (c) and (d) indicate the position of the vertical cross-sections shown in Figure 8. The dashed box regions in (c) and (d) are enlarged in (e) and (f), respectively.
Figure 8. Vertical cross sections through the lines (a) AB, (b) A1B1, (c) A2B2, (d) A3B3, (e) A4B4, and (f) A5B5 in Figure 7c-f. Shown are temperature (shaded, °C), wind vectors, vertical velocity (blue contours, with contour levels at 0.5, 1, 2, and 5 m s⁻¹), and 45 dBZ radar reflectivity (red contours).
Figure 9. The same as in Figure 7, but for times at (a, b) 0830 and (c, d) 0900 UTC 28 June 2013. The lines in (c) and (d) indicate the position of the vertical cross-sections shown in Figure 10. The dashed box regions in (c) and (d) are enlarged in (e) and (f), respectively.
Figure 10. The same as in Figure 8, but for vertical cross sections through the lines (a) CD, (b) C1D1, (c) C2D2, (d) C3D3, (e) C4D4, and (f) C5D5 in Figure 9c-f.
Figure 11. Fields shown are the same as in Figure 7 but for experiment with the mountains within the basin removed (NoMidMts) at times of (a, b) 0300, and (c, d) 0900 UTC 28 June 2013.
Figure 12. Fields shown are the same as in Figure 7 but for experiment with the mountains on the north side of the basin removed (NoNorthMts) at times of (a, b) 0300, and (c, d) 0900 UTC 28 June 2013.
Figure 13. Time evolution of (a) temperature (shaded) and convergence (blue contours, $> 0.5 \times 10^{-3} \text{s}^{-1}$ filled with slashes), or (b) cross-line horizontal wind speed (shaded) and vertical velocity (blue contours, $> 0.1 \text{ m s}^{-1}$ filled with slashes) during stage I along line AB in Figure 7c at 0.25 km MSL. The same as (a) and (b), respectively, (c) and (d) are for experiment NoMidMts, and (e) and (f) are for experiment NoNorthMts. The 45 dBZ composite radar reflectivity shown as red contours filled with dashed lines outline the convective lines.
Figure 14. The same as Figure 13, but during stage II, along line CD in Figure 9c at 0.5 km MSL. The initiation of convective lines in (c-d) and (e-f) is about 1 hour earlier than that in (a-b).
Figure 15. The conceptual model of convective line formation during (a) stage I and (b) stage II. The warm southerly airflow boundary or the south leading edge of the Meiyu front, the cold outflow center, and the cold outflow boundary are shown as red bold, blue, and blue-dashed lines, respectively. The main convection region, the main stratiform region, and the cloud boundary are outlined with red-dashed, orange, and green-dashed lines, respectively. Red ellipses embedded with small ovals indicate the convective lines, with a wider one denoting a stronger convective line. Small red ellipses represent the convection ahead of the Meiyu front. The motion of the convective cells along the convective line and the motion of the convective lines primarily following the mid-level flow are denoted with bold arrows. Terrain height is shaded, and the main mountains are labeled in (a). Important low-level wind vectors are shown, and the black ellipse in (a) indicate a sustained low-level convergence on the lee side of the mountains Wugong.