Observational and dynamic downscaling analysis of a heavy rainfall event in Beijing, China during the 2008 Olympic Games

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Abstract
A local precipitation event with several dispersedly distributed heavy rainfall centers exceeding 50 mm occurred in Beijing, China on 14 August 2008 during the Beijing Olympic Games. The heavy rainfall event was produced by a few scattered convective storms. Detailed observational analysis with data from automatic weather stations (AWSs) as well as the meteorological radar in Beijing and a dynamic downscaling analysis with a diagnostic model, California Meteorological Model (CALMET), showed that convergence zones caused by small-scale topography and colliding outflow boundaries were key influencing factors in the initiation and development of the convective storms. Convergence helped to induce upward vertical motion as well as concentrate moisture to reduce the convective inhibition (CIN). Horizontal wind speed may modulate the effectiveness of convergence. Downscaled wind fields by CALMET not only retain the overall features of the original fields, but also present more detailed structures, especially near complex terrain, which is much helpful in analyzing and predicting the development of the storms.

Keywords: local heavy rainfall; convergence; outflows; topography; observational analysis; dynamic downscaling analysis

1. Introduction
The initiation and development of local convective storms and consequent heavy precipitation are determined by a combination of multiple-scale factors. Under favorable synoptic environment, local convergence is one of the significant factors influencing the formation and organization of convective storms and precipitation (Byers and Rodebush, 1948; Wilson and Schreiber, 1986; Wilson and Megenhardt, 1997). Outflows produced by precipitation systems can contribute to the development of convergence zones (Wilhelmsen and Chen, 1982). Previous studies on outflows have given more attention to those produced by highly organized convective systems, while the outflows produced by localized, scattered convective storms, and their roles in the formation of new storms still lack detailed analysis. In the vicinity of complex terrain, the formation of convective storms and precipitation could also be modulated by local topography, making the situation more complicated. Houze (2012) summarized four possible orographic effects in convective precipitation.

Beijing is characterized by local complex terrain with the Yan Mountains to the north and the Taihang Mountains to the west with heights varying from 200 to 1600 m (Figure 1(a)). Relatively smooth terrain with low elevations dominates the central and southeast parts of Beijing where ‘unexpected’ (in the current observational network) local convective storms and consequent short-term local heavy rainfall often occur, being a big challenge to the forecasters. An unusual local heavy precipitation event produced by some scattered convective storms on 14 August 2008 during the Beijing Olympic Games provides a perfect case to investigate the local conditions related to the formation and organization of local convective storms and heavy rainfall centers.

An overview of this heavy rainfall event is given in Section 2. In Section 3, observational analysis using data from the automatic weather stations (AWSs) as well as the meteorological radar in Beijing is performed, followed by a dynamic downscaling analysis with a diagnostic model, California Meteorological Model (CALMET), to show the formation and organization of the local convective storms and consequent rainfall centers. A summary is given in Section 4.
3. Observational analysis

Zhang et al. (2014) analyzed the evolution of the formation location of storms in this event, and emphasized the importance of the boundary-layer convergence which existed more than half an hour before the emergence of several storms. They also pointed out that local topography and outflows from pre-existing thunderstorms played a crucial role in the event. However, the following questions remain unsolved. (1) How was the boundary-layer convergence generated in detail under the impact of local topography and the outflows? (2) What was the detailed role of convergence in the formation of convective storms? (3) There were some convergence zones without deep convections in this event in Beijing. What were the possible reasons?

With the assistance of data from the AWSs and a diagnostic model, CALMET, we try to address the above problems in this section.

3.1. Observational analysis using data from AWSs and radar

Several isolated storms were important origins of the heavy rainfall (see storms with labels in Figure 2). At 0254 UTC on 14 August 2008, besides the relatively extensive radar reflectivity to the southwest of Beijing and some scattered cells in Mentougou, a separate storm cell (‘A’ in Figure 2(a)) with reflectivity over 45 dBZ emerged in Pinggu. Upslope flows converging in the north of Pinggu contribute to the initiation of cell A (Figure 2(a) and 3(b)). The outflows from the southwest precipitation system enhanced the local convergence in Daxing. Another significant contributor to the convergence in Daxing is the southwestwards-running flows through the river valley of Miyun, which were partly induced by the convective activity to the northeast of Beijing.
Figure 2. Vertical maximum reflectivity (dBZ) observed by Beijing radar at (a) 0254, (b) 0300, (c) 0312, (d) 0330, (e) 0348, (f) 0400, (g) 0418, and (h) 0448 UTC. Black capital letters give numbers to the cells described in the text. Brown lines are isohypses of 200 m; similarly for the rest of figures.
Beijing under the favorable large-scale environment of the 500-hPa low (not shown). Accordingly, a new separate cell (‘B’ in Figure 2(b)) emerged in Daxing at 0300 UTC and developed fast in the next 10 min (Figure 2(c)). Distinct local heavy precipitation started to occur in Daxing after the formation of cell B and lasted for less than 2 h (Figure 4(a) and (b)). Accumulated 1-h rainfall amount of 51.1 mm was recorded in the Daxing station from 0300 to 0400 UTC. Another separate cell (‘C’ in Figure 2(c)) with reflectivity over 40 dBZ ensued in Pinggu near the 200-m isohypse at 0312 UTC, which was triggered by the local convergence in the south of Pinggu (Figure 3(d)). With the development of the local precipitation system in Daxing, an apparent cold pool with relatively drier air (indicated by purple circles in Figure 3(e)–(h)) was generated and corresponding outflows were formed. With the further expansion of the cold pool in Daxing, the local convergence zone was pushed to the Daxing–Tongzhou border (Figure 3(e)–(h)), contributing to the following formation and development of local convective storms there. At 0330 UTC, a new separate cell with reflectivity over 40 dBZ was observed in the west of Tongzhou (‘D’ in Figure 2(d)). As the cells in Pinggu continued to develop, interaction between the outflows near Pinggu and the northeasterly along the river valley of Miyun formed a local confluence zone near the 200-m isohypse near the border of Shunyi and Miyun, which triggered the cell G and the cell H (Figure 2(e) and (f)). With the development and merger of cells A, C, and H, a distinct rainfall center of hourly precipitation over 20 mm was observed near the border of Shunyi, Pinggu, and Miyun from 0400 to 0500 UTC (Figure 4(b)).

It is noticeable that distinct convergence was found in the center of Shunyi (as indicated by the convergence of streamlines in Figure 3(b), (d), (f), and (h)), but no convective storm developed. Horizontal wind speed was relatively large in the center of Shunyi (not shown). It may make the updraft associated with the convergence more tilted and more vulnerable to entrainment (Markowski et al., 2006). Sounding at the southern observatory shows that it was drier at the upper boundary layer than at the surface, thus entrainment was unfavorable for the development of deep convective clouds.

At 0348 UTC, two separate storm cells with reflectivity over 40 dBZ were also seen in the south of Huairou (‘E’ in Figure 2(e)) and in the north of Changping (‘F’ in Figure 2(e)), which were related to the small-scale convergence zone under local complex terrain and the surface small-scale cyclonic circulation near local fork horn shaped topography, respectively (Figure 3(h), also can be seen in the following analysis by CALMET). Convergence could be seen in the north of Changping around 0300 UTC, and convection was detected by the radar at 0348 UTC. Convergence could induce upward vertical motion to lift parcels to reach their level of free convection (LFC). Were there any other factors influencing the formation of the convection? As shown in Figure 5, the 2-m mixing ratio observed in the Taipingzhuang station (denoted by the red dot in Figure 1(a)) near the convergence area presented an increasing trend before the development of the cell F in Changping. It illustrates that convergence in the north of Changping also assisted in moisture pooling, which reduced CIN there. The combined effect of upward vertical motion and increasing moisture led to the formation of the cell F (Figure 2(e)) at 0348 UTC in Changping.

At 0415 UTC, cold pools and outflows near Daxing and Pinggu (indicated by purple circles and dark blue circles respectively in Figure 3(i) and (j)) grew rapidly as the storms and related local precipitation systems developed and decayed. In the meantime, the southeasterly winds between Daxing and Pinggu enhanced significantly, and the previous flow along the river valley of Miyun was almost totally cut off. Two new cells, I and J, began to form between E and F along the slantwise terrain in the northwest of Beijing. The combination of the southeasterly winds and the slantwise terrain, as well as convergence resulting from the colliding boundary between E and F contributed to the formation of cell I and J (Figure 2(g)). These convective storms induced the local precipitation in Changping from 0400 UTC (Figure 4(b)). With the enhancement of the outflows in Daxing and Pinggu, a new cell (‘K’ in Figure 2(g)) in the north of Tongzhou formed at the convergence zone between the two outflows. Later at 0445 UTC (Figure 3(k) and (l)), the cold pools near Pinggu and Daxing continue to enlarge. The outflows from Shunyi, Miyun, Pinggu, and from Daxing converged with the outflows from the four storm cells (E, F, I, and J) forming in Huairou and Changping previously. Thus, a local intense convergence zone developed along the 200-m isohypse in the northwest of Beijing (Figure 3(i)). The above cells (E, F, I, and J) began to merge and develop along the convergence zone, and a small-scale line convection was to be organized in the northwest of Beijing (Figure 2(h)). With the development and southwestwards movement of these convective systems (Figure 2(i) and (j)), precipitation increased sharply in Huairou and Changping from 0500 UTC and formed the most notable rainfall centers along the 200-m isohypse (Figure 4(c)). The 47.9-mm rainfall amount in Bohai station and 46.8-mm rainfall amount in Changping station were recorded from 0500 to 0600 UTC.

### 3.2. Downscaling analysis of surface wind fields

As analyzed in Section 3.1, the formations of the convective cells E and F were closely related to small-scale topography. However, the detailed formation processes could not be clearly recognized due to the spatial resolution of the current observational network (Figure 1(a)). Thus, a dynamic downscaling analysis using a diagnostic model, CALMET, was conducted below by using the AWS observations. CALMET is a component of the California Puff (CALPUFF) Modeling System which is an advanced...
Figure 3. Distributions of potential temperature (K) (left), and mixing ratio (g kg$^{-1}$) superimposed by surface streamlines (right), observed by the AWSs at (a) and (b) 0250, (c) and (d) 0305, (e) and (f) 0330, (g) and (h) 0345, (i) and (j) 0415, (k) and (l) 0445 UTC, respectively. Red stars denote stations where rainfall was recorded during the past 5 min. Purple circles indicate the cold pools in Daxing, and dark blue circles indicate the cold pools in Pinggu.
Figure 3. Continued.
nonsteady-state meteorological and air quality modeling system. CALMET has been widely applied to wind resource assessment (Yim et al., 2007; Mari et al., 2011), which is composed of a diagnostic wind field module and micrometeorological modules. It takes two steps for CALMET to approach the downscaling of wind fields. First, an initial-guess wind field from observations or mesoscale model output is adjusted according to kinematic effects of terrain, slope flows, and terrain blocking effects. Second, an objective analysis procedure is performed. Additionally, smoothing, O’Brien procedure and divergence minimization are optional (Scire et al., 2000). Evaluations showed that when there were plentiful observational stations, CALMET could generate reasonable high-resolution wind fields, retaining original features of observations (Cox et al., 2005; Wang and Shaw, 2009). A diagnostic domain of 60 km × 60 km with a resolution of 100 m in CALMET was set up in this work (The red box in Figure 1(a)). 1-arc-second (~ 30 m) ASTER Global Dem (ASTER GDEM) terrain data [A product of the Ministry of Economy, Trade and Industry of Japan (METI) and the National Aeronautics and Space Administration (NASA)], and 1-km US Geological Survey (USGS) Global Land Use and Land Cover Data were used as input to help reveal the detailed effect of topography in the northwest of Beijing. The initial-guess wind fields were produced using hourly observations from the AWSs in Beijing.

More details of interactions between fine-scale complex terrain and local flows were showed in the downscaled wind fields (Figure 6(b) and (d)) than in the original fields (Figure 6(a) and (c)). The cell F in Changping (Figure 2(g)) was triggered and developed under complex terrain (Figure 1(a)). In the background of 1-arc-second (~ 30 m) resolution terrain, a cyclonic circulation (the red rectangle in the lower-left corner of Figure 6(d)), in which fine-scale convergence zones related to fine-scale terrain variation were embedded, was more clearly showed to develop in the vicinity of inverted V-shaped terrain in Changping. Cell F formed and grew near the surface cyclonic circulation. And in the meantime, intense directional convergence of wind vectors (the wind vectors on either side nearly blew toward each other) could be much clearly seen in the southwest of Huairou after downscaling (The red rectangle in the upper-right corner of Figure 6(b) and (d)), which sustained the formation and development of the cell E in Huairou. It is notable that the convergence of local upslope flows related with cell E could not be recognized from the original AWS observational network shown in Figure 6(a) and (c), in which the wind vectors were more uniform.

CALMET not only retains general features of the original wind fields, but also presents more detailed structures and helps to understand the role of local topography in the formation and development of local convective storms.
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4. Summary

A local heavy precipitation event with several dispersely distributed heavy rainfall centers exceeding 50 mm occurred in Beijing, China on 14 August 2008 during the ongoing Olympic Games. The heavy rainfall event was produced by a few scattered convective storms. In this article, detailed observational analysis with data from the AWSs as well as the Doppler radar in Beijing and a dynamic downscaling analysis with the diagnostic model, CALMET, were performed to examine the initiation and development of the local convective storms and consequent precipitation. Some results were obtained.

1. Detailed observational analysis showed that convergence zones attributed to small-scale topography and colliding outflow boundaries were of vital importance in the development of those initial convective storms in this event. Convergence helped to induce upward vertical motion as well as concentrate moisture to reduce CIN. Horizontal wind speed may modulate the effectiveness of convergence and associated updraft, thus affecting the formation of convective storms.

2. The downscaled wind fields by CALMET not only retain the overall features of the original flow fields, but also present more detailed structures, especially in complex terrain. And some of the details could not be clearly recognized in the original fields.

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