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The Beijing extreme rainfall of 21 July 2012: "Right results" but for wrong reasons

Da-Lin Zhang,[1,2] Yonghui Lin,[1] Ping Zhao,[1] Xiaoding Yu,[3] Songqiu Wang,[1] Hongwen Kang,[1] and Yihui Ding[4]

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[1] The heaviest rainfall in 6 decades fell in Beijing on 21 July 2012 with a record-breaking amount of 460 mm in 18 h and hourly rainfall rates exceeding 85 mm. This extreme rainfall event appeared to be reasonably well predicted by current operational models, albeit with notable timing and location errors. However, our analysis reveals that the model-predicted rainfall results mainly from topographical lifting and the passage of a cold front, whereas the observed rainfall was mostly generated by convective cells that were triggered by local topography and then propagated along a quasi-stationary linear convective system into Beijing. In particular, most of the extreme rainfall occurred in the warm sector far ahead of the cold front. Evidence from a cloud-permitting simulation indicates the importance of using high-resolution cloud-permitting models to reproduce the above-mentioned rainfall-production mechanisms in order to more accurately predict the timing, distribution, and intensity of such an extreme event.
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1. Introduction

[2] An extreme rainfall event hit Beijing during the period of 1000 BST (or 0200 UTC) 21–0400 BST 22 July 2012 with a record amount of 460 mm in Fangshan (Figure 1a). Several rain gauge stations received hourly rainfall rates exceeding 85 mm (see Figure 1b for an example). This extreme event, generated by a linear-shaped mesoscale convective system (MCS), inundated many roads with trapped cars and buses as well as collapsed buildings in waist-deep water. It left 79 dead resulting from drownings, lightning, electrocutions from downed power lines, and landslides in the western mountainous regions, and cost nearly $2 billion in direct economic losses, making it a high-impact event internationally.

[1]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China.
[2]Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA.
[3]Training Center, China Meteorological Administration, Beijing, China.
[4]National Meteorological Center, China Meteorological Administration, Beijing, China.

Corresponding author: D.-L. Zhang, Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742–2425, USA. (dalin@atmos.umd.edu)

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[3] It was encouraging that the Beijing Meteorological Bureau (BMB) predicted 24 h in advance a total of likely up to 100 mm rainfall to begin in the early evening of 21 July until the morning hours of 22 July, albeit much smaller in intensity and several hours later than the observed, and then BMB issued its first orange (i.e., the second to the most severe red color coding) rainstorm alert warning since 2005. This timely and encouraging forecast was based on the China Meteorological Administration/National Meteorological Center's (CMA/NMC) operational numerical weather prediction (NWP) model (T639L60) in the light of other operational centers' model predictions available at the time. (The CMA/NMC model has a horizontal grid resolution of 0.28125° and 60 levels in the vertical, and uses a mass flux–based convective scheme and a prognostic cloud water equation [*Guan et al*. 2008; *Jung et al*. 2010].) As Figure 1a shows, the model predicts more than 150 and 100 mm rainfall in north-central Hebei Province and western Beijing that will be shown in association with local topography and a cold frontal passage, respectively. In fact, several operational centers' global ensemble models predict over 50% probability of 50–100 mm rainfall in northern China 3–4 days in advance [*Grumm*, 2012], although for some forecasts 12 h later than that observed. Although the predicted maximum rainfall is about 100 km too far to the southwest of the observed, the commonly viewed high predictability of such "frontal-related"rainfall by several NWP models gave considerable confidence to local forecasters for issuing severe rainstorm warnings.

[4] While the operational models provided an important guidance for this extreme rainfall event, we show below that these "right" results were generated by the operational NWP models for wrong reasons. The next section describes favorable larger-scale conditions for the extreme rainfall production. Section 3 shows the topographical triggering and subsequent echo training of deep convection [*Doswell et al*., 1996] that accounted for the formation of the linear MCS in relation to the passage of the cold front. Section 4 discusses the model prediction and the limitations of the current coarse-resolution NWP models. In particular, one of the cloud-permitting ensemble simulations of the case will be used to demonstrate the required model physics configurations for predicting such an extreme rainfall event. A more detailed study of the case will be deferred to a forthcoming journal article.

2. Larger-scale Conditions

[5] Figure 2a shows the 850 hPa large-scale circulations at 1400 BST when heavy rain just began in southwesterly monsoonal flow with high equivalent potential temperature

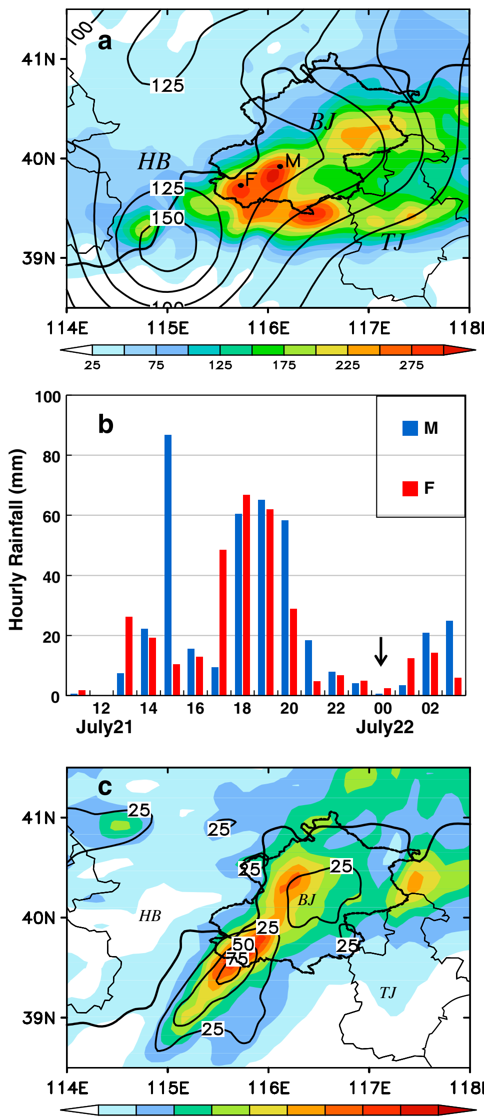

Figure 1. (a) Comparison of the 24 h accumulated rainfall (mm), ending 0800 BST 22 July 2012, between the observed (shaded) and the predicted (contoured at 25 mm intervals) by the CMA/NMC operational model that was initialized at 2000 BST 20 July 2012. (b) Time series of rain gauge observations (mm h^{-1}) at Fangshan (red) and Mengtougou (blue) during the period of 1100 BST 21–0300 BST 22 July. Letters “F” and “M” denote the locations of rain gauge stations at Fangshan (39.73°N, 115.73°E) and Mengtougou (39.94°N, 116.11°E), respectively. An arrow is used to indicate the timing of the frontal passage. (c) The 24 h accumulated rainfall (mm, shaded) ending 0800 BST 22 July, and the three-hourly rainfall (contoured at 25 mm intervals) ending at 2000 BST 21 July, from an ensemble member of WRF cloud-permitting simulations initialized by the NOAA/National Centers for Environmental Prediction (NCEP) Global Forecast System operational analysis at 1400 BST 20 July but with assimilated conventional observations at 2000 BST 20, 0000, and 0800 BST 21 July. The simulated cold front is about to enter the plotting domain from the northwest at 2000 BST 21 July. Dark solid lines denote the terrain height of 1000 m associated with Mt. Taihang. The metropolitan city of Beijing and Tianjin, and Hebei Province are indicated by “BJ,” “TJ,” and “HB,” respectively.

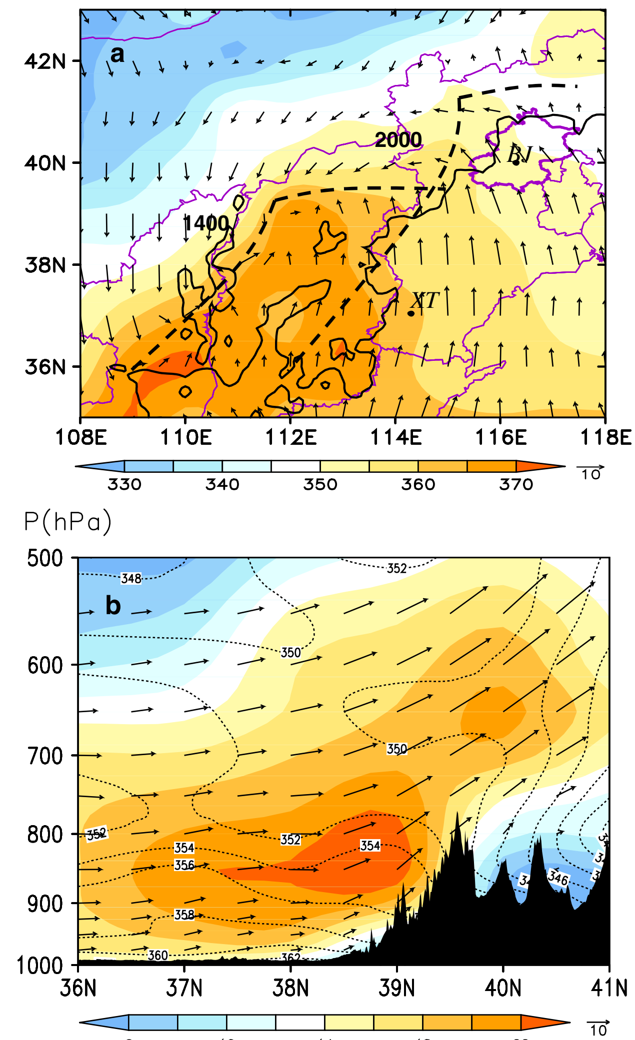

Figure 2. (a) Distribution of the equivalent potential temperature (θ_e) at $z = 500$ m (shaded), superimposed with 850 hPa flow vectors, from the NOAA/National Centers for Environmental Prediction (NCEP) 1° × 1° final analysis at 1400 BST 21 July 2012. Dashed lines denote the evolution of a trough axis and a wind-shear line at 850 hPa at 1400 and 2000 BST 21 July. Dark solid lines denote the (5 km resolution) terrain height of 1000 m associated with Mt. Taihang. Beijing and Xingtai are indicated by “BJ” and “XT,” respectively. (b) North-south vertical cross section of θ_e (dotted lines) at intervals of 2 K and the moisture flux, $|\mathbf{V}|\, q_v$ (color shadings, g m^{-1} kg s^{-1}), where $\mathbf{V}$ is the horizontal wind vector and q_v is the mixing ratio of water vapor, superimposed with in-plane flow vectors (vertical motion is multiplied by 5) along the longitude of 114.5°E at 1400 BST 21 July 2012. Topography associated with Mt. Taihang at 5 km resolution is shaded in black.

(θ_e) in the planetary boundary layer (PBL) over the eastern plain region of China and a northwesterly lower-θ_e flow behind a cold front. We see a northeast-southwest–oriented trough axis associated with the cold front, which moved toward Beijing at a speed of 12–15 m s^{-1}, and a well-defined zonally oriented wind-shift line moving northward into southern Beijing. An examination of the 850 hPa flow fields reveals that the cold front slowed its eastward movement due to the topographical blocking as it propagated across Mt. Taihang, over which a large portion of landmass exceeds 1500 m (Figure 2b), and it accelerated after passing it. The approaching of Typhoon Vincent from South China Sea to Guangdong Province has altered the southwesterly monsoonal flow ahead of the front by weakening it in central China (not shown) and shifting it to a southerly flow to form the wind-shift line. This alteration of moisture supply appeared to reduce the frontal rainfall in central China [*Grumm*, 2012]. *Chen et al.* [2012] have provided a more detailed description of the large-scale conditions associated with the Beijing extreme rainfall event.

[6] A south-north vertical cross section of moisture fluxes, θ_e, and in-plane flow vectors is given in Figure 2b, showing the presence of a low-level jet (LLJ) at 850 hPa, albeit about 8 m s^{-1}, as also indicated by Xingtai's sounding (Figure 3a). More importantly, we see pronounced upward motion with large northward moisture (and θ_e) fluxes as the southerly flow hit the steep terrain of Mt. Taihang at nearly a right angle. This topographical lifting appeared to be even greater as the south-to-southeasterly LLJ of 10–12 m s^{-1} to the east of Xingtai overran the southwest-northeast–oriented terrain in the 38.5–40.5°N range, which is roughly estimated by the terrain slope and horizontal flows to be about 20 cm s^{-1}. Evidently, this regional topographical lifting must have played an important role in spawning convective cells for the formation of the MCS, as will be seen in the next section.

[7] An observed sounding taken at an early morning hour at Xingtai (Figure 3a), which is located just at the foothill of Mt. Taihang and about 400 km upstream from Beijing, exhibits conditional instability with the convective available potential energy (CAPE) of about 1950 J kg^{-1} and a deep moist layer of high relative humidity (85–90%) up to 400 hPa with an estimated precipitable water amount of over 60 mm [also see *Grumm*, 2012; *Chen et al.*, 2012]. We may expect this CAPE to be much greater after the PBL became well developed during the early afternoon hours. The high moisture content in a deep layer and continuous energy supply were clearly the necessary conditions for the generation of torrential rainfall in terms of high precipitation efficiency and the maintenance of conditional instability [*Trier et al.*, 2006; *Zhang and Zhang*, 2012]. Although there existed a small amount of convective inhibition energy (CIN), an air parcel in the PBL, e.g., at 925 hPa, could easily reach the level of free convection (LFC, at 875 hPa) after slight lifting, indicating the readiness of convective initiation with a low cloud base. Furthermore, Xingtai's sounding shows an environment of weak winds veering with height (implying warm advection), i.e., less than 10 m s^{-1} up to 200 hPa, and weak vertical wind shear, which were all favorable for heavy rainfall in the warm sector [*Maddox et al.*, 1979; *Zhang and Fritsch*, 1986; *Schumacher and Johnson*, 2005].

[8] It is evident from Figures 2 and 3a that in spite of the low LFC and a deep layer of moist air in the warm sector, significant lifting to remove the CIN near the top of the PBL was lacking, even in a deep layer, during the northward transport of the low-level high-θ_e air over the eastern plain region until it hit that portion of Mt. Taihang, so the near 39°N portion of Mt. Taihang may be regarded herein as the convective spawning region.

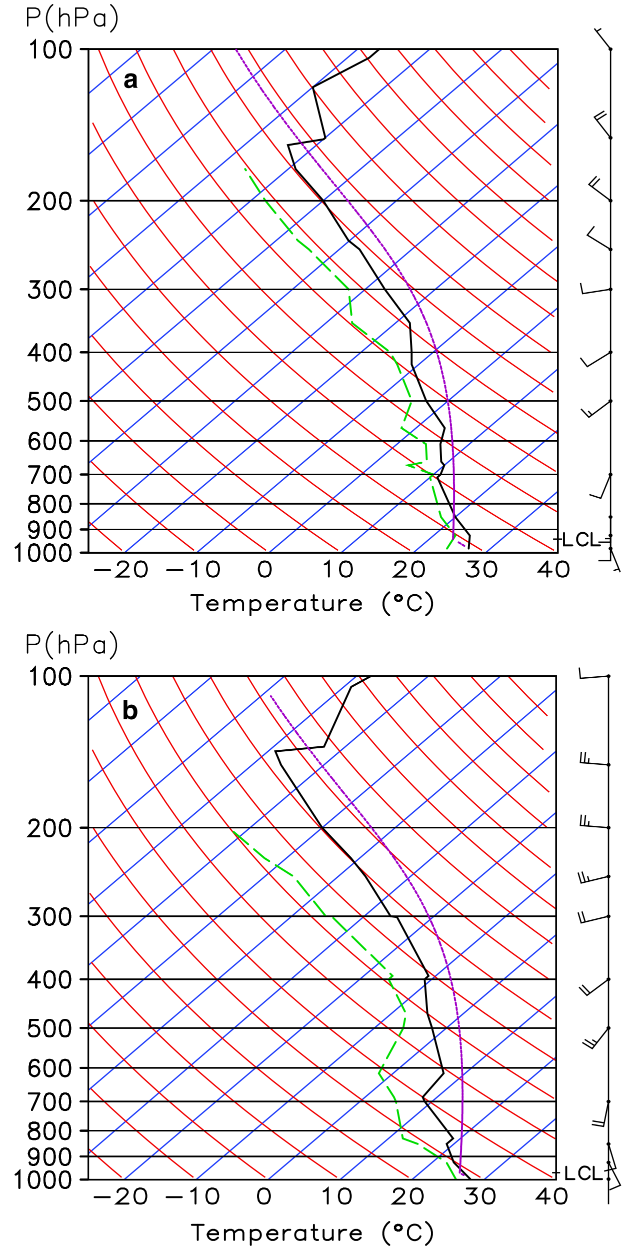

Figure 3. Skew T-log$P$ plots of the soundings taken at (a) 0800 BST 21 July at Xingtai (37.07°N, 114.50°E), Hebei Province, and (b) 1400 BST 21 July 2012 at Beijing (39.80°N, 116.47°E), which is located about 35 km to the southwest of Mentougou.

3. Backbuilding and Echo Training of Deep Convection

[9] An examination of satellite images and national composite of radar reflectivity indicates the development of convective clouds ahead of the large-scale cold front long before the formation of the MCS causing the extreme rainfall. At 1100 BST, the MCS has already formed in isolation, which was located at least 500 km to the east of the cold front (cf. Figures 2a and 4a). Its leading convective portion was linear, with two areas of higher radar reflectivity (i.e., >50 dBZ at Fangshan and Mengtougou), marking the beginning of extreme rainfall in southwestern Beijing. The northern portion of the leading convective line was relatively weak

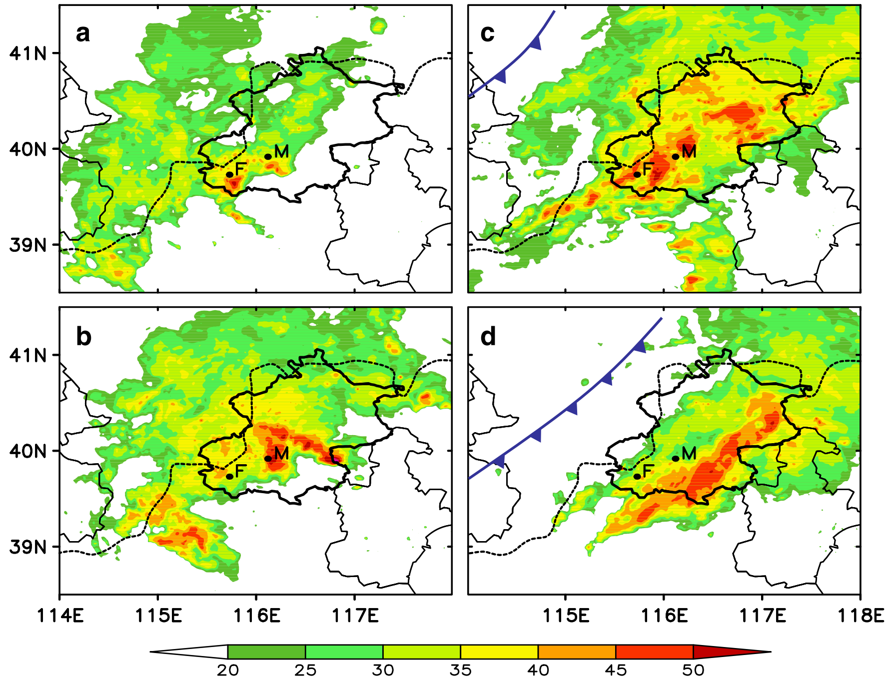

Figure 4. Composite radar reflectivity (dBZ) based on radar data at sites Beijing and Tianjin at (a) 1100, (b) 1400, (c) 1700, and (d) 2000 BST 21 July 2012. The surface frontal position and the terrain height of 1000 m (dotted) are also shown. Letters "F" and "M" denote the locations of heavy rainfall received at Fangshan and Mengtougou, respectively.

with radar echoes of less than 35 dBZ, due likely to the presence of much lower-θ_e air to the north of the wind-shift line. Similarly, a large coverage of mixed convective-stratiformclouds took place over the western high mountains, as denoted by the 1000 m contour, which resulted from the topographical lifting and then advection of the southerly flows into a lower-θ_e high-mountain region (cf. Figures 2b and 4a).

[10] By 1400 BST, part of Beijing began to experience moderate rainfall with heavier amount occurring in the vicinity of Mengtougou (cf. Figures 1b and 4b). Note the development of two northwest-southeast–oriented rainbands that appeared to be associated with the wind-shift line where pronounced convergence was present (cf. Figures 2a and 4b). As the wind-shift line and the associated convection moved to northern Beijing (Figure 4c), the low-level flow became more southerly (Figure 3b). The extremely moist PBL with an LFC of 200–300 m and large CAPE explains well the development of deep convection in central Beijing with little needed lifting. Meanwhile, convective cells were seen being spawned by Mt. Taihang near 39°N (Figures 4a–4c) and then propagating northeastward along the same path into Beijing. These scenarios are very similar in heavy rainfall production to the backbuilding and echo-training processes associated with another torrential rainfall event in East China [*Zhang and Zhang*, 2012], and the heavy rainfall climatology in North America [*Schumacher and Johnson*, 2005], except for the topographical triggering mechanism. Although the linear MCS had a trailing stratiform precipitation region during the earlier stages (Figures 4b and 4c), it gradually transformed into a convective line-parallel statiform configuration at the later stages [*Parker and Johnson*, 2004], as the wind-shift line moved northward (cf. Figures 2a, 4c, and 4d).

[11] At 1700 BST, the cold front has moved 100–120 km to the west of Beijing, but with little rainfall associated with it due likely to its location in the wake of the MCS (Figure 4c). In contrast, the linear MCS became well developed at this time and remained quasi-stationary during the past few hours due to the presence of weak larger-scale westerly flow in the warm sector. As compared to weaker echoes over the western high mountains at the earlier stages (Figure 4a), rainfall intensity was now seen being increased by a deep layer of southerly moisture supply, with increasing width northeastward, as convective cells were "training" along the leading line from their spawning region. Clearly, this echo-training process accounted for the generation of more than 50 mm h^{-1} rainfall rates at Fangshan, Mengtougou (cf. Figures 1b and 4c) and several other stations, and this quasi-stationary MCS stage appeared to be the most critical one contributing to the extreme rainfall.

[12] Subsequently, the linear MCS began to propagate southeastward out of Beijing. As a result, rainfall rates at stations from the southwest to northeast of Beijing decreased rapidly after 2000 BST (cf. Figures 1b and 4d). On the other hand, some new convective cells were initiated along the cold front (Figure 4d), and their subsequent growth accounted for pronounced rainfall after 0100 BST 22 July (Figure 1b). A surface analysis indicates the roles of convectively generated cold pools in displacing the MCS, which is typical during the later stages of the backbuilding and echo-training processes [*Schumacher and Johnson*, 2005, 2008].

[13] When comparing the rain gauge to radar observations (Figures 1b and 4), we can see three rainfall generation stages. Rainfall began at 1100 BST in southwestern Beijing and reached the first peak at 1500 BST, which was likely caused by the northward movement of the wind-shift line. This was followed by a 1.5 h weakening stage, and then a second rainfall peak occurred at 1800–1900 BST as a result of echo-training convective cells in the linear MCS. Rainfall decreased rapidly after 2000 BST as the MCS moved out of Beijing. The passage of the cold front accounted for the third heavy rainfall period

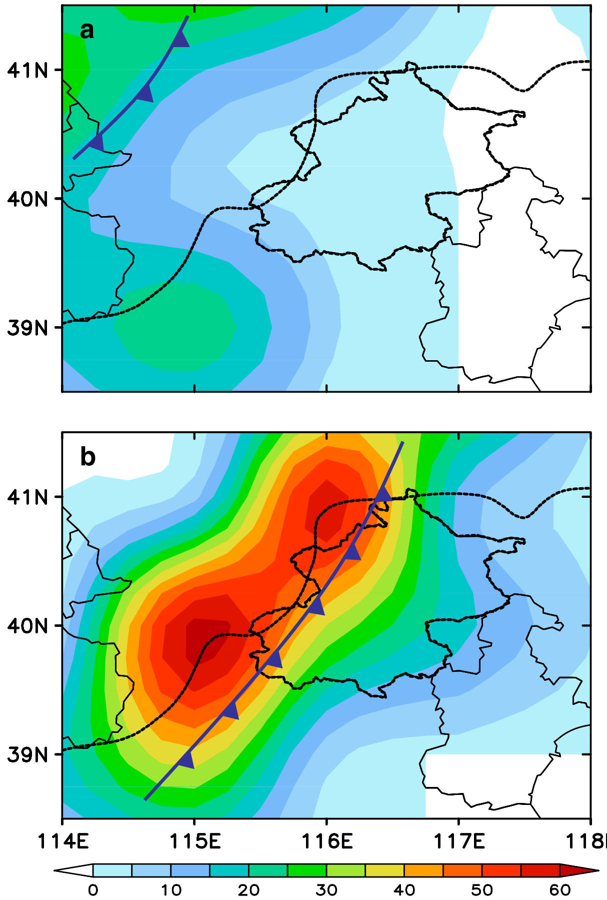

Figure 5. The CMA/NMC T639L60 forecasts: three-hourly rainfall (mm) ending at (a) 2000 BST 21 and (b) 0500 BST 22 July 2012 with the model initialized at 2000 BST 20 July 2012. The predicted surface frontal position and the terrain height of 1000 m (dotted) used by the model are also shown.

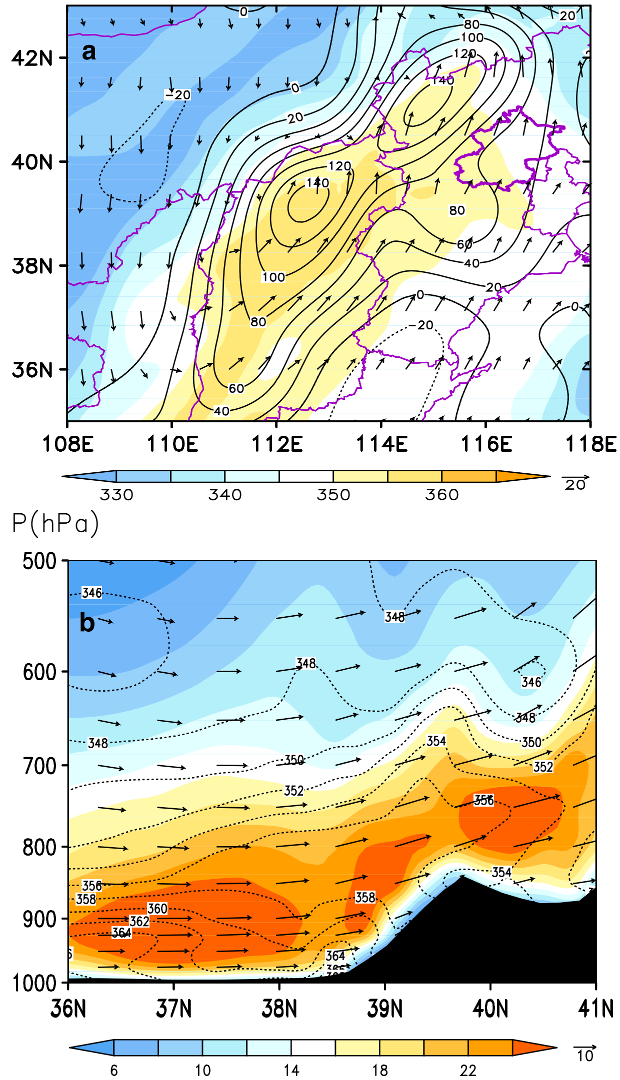

Figure 6. The CMA/NMC T639L60 24 h forecasts valid at 2000 BST 21 July 2012: (a) the equivalent potential temperature (θ_e) field at $z = 500$ m (shaded), the 700 hPa vertical motion (solid/upward, dashed/downward) at intervals of 0.2 m s^{-1}, and flow vectors; (b) as in Figure 2a but along the longitude of 114.8°E.

commencing at 0000 BST 22 July. However, rainfall intensity was much weaker and duration was shorter than that earlier.

4. Numerical Weather Prediction and Required Model Configurations

[14] Apparently, predicting the above three rainfall regimes with different mechanisms is challenging to today's coarse-resolution NWP models with parameterizd convection. To see this point, the CMA/NMC-predicted three-hourly rainfall amounts at two representative times are given in Figure 5, showing an area of topographically generated rainfall centered at 39°N, 115°E, ending at 2000 BST 21 July, that is similar to the observed except for the overpredicted coverage and underpredicted amount (cf. Figures 1a and 5a).This terrain-induced rainfall continues until the arrival of the cold front, accounting for the excessive 24 h accumulated rainfall in north-central Hebei Province. However, this rainfall remains localized and does not extend northeastward due to the absence of a large quantity of grid-scale cloud hydrometeors [*Zhang et al.*, 1988; *Molinari and Dudek*, 1992; *Zhang et al.*, 1994].

[15] Similarly, the model predicts an elongated rainfall band and updrafts of greater than 1.4 m s^{-1} on the west of Beijing in association with the cold front (Figures 5b and 6a), which is as expected 8–12 h later than the observed. This rainfall band could be understood as a result of the frontal lifting of a deep layer of available high moisture content (or θ_e air) that has not been previously released by any convective processes (see Figures 6a and 6b). In nature, much less rainfall occurred during the frontal passage, because most of the environmental CAPE and moisture content ahead of the cold front has been removed by the linear MCS. Thus, we may state that any NWP model (even in a research mode) failing to reproduce the echo-training process would miss significantly the timing (e.g., 8–12 h herein), location (e.g., 100–150 km), and magnitude (50%) of the present extreme rainfall event. Of course, the approaching frontal circulations might have enhanced the rainfall production through increased moisture supply and lifting in the warm sector, especially during the second heavy rainfall stage.

[16] It is obvious that reproducing the periodic initiation of convective cells over the sloping mountains and their subsequent propagation along the same path requires the use of high-resolution (e.g., up to 1–5 km) cloud-permitting NWP

models with realistic cloud microphysical schemes. To demonstrate this point, we have performed 30-member ensemble simulations with the triply nested grid (40.5/13.5/4.5 km) and 35 vertical levels, version 3.4 of the Weather Research and Forecast (WRF) [*Skamarock et al*., 2005] model, following the ensemble Kalman filter data assimilation approach of *Bei and Zhang* [2007]. The simulations in the two innermost domains use the *Thompson et al*., 2008 single-moment six-class microphysics scheme with convective parameterization bypassed. Results indicate that almost all the ensemble members reproduce the linear MCS in the warm sector to some degree, to be shown in a forthcoming journal paper. An example from a member of the ensemble simulations is given in Figure 1c, showing the simulated 24 h accumulated total rainfall of more than 250 mm and, more importantly, the three-hourly linear-shaped rainfall amount of more than 75 mm in the warm sector. Recognizing the use of improved initial conditions through assimilated conventional observations, higher horizontal resolution, and better model physics representations, we can see that the intensity, distribution, and timing of the extreme rainfall event from this member simulation all compare much more favorably than those in the NMC forecasts (cf. Figures 1a and 1c). Nevertheless, none of the 30-member simulations could reproduce the local rainfall rates of over 80 mm h^{-1}. This could be attributed to the cloud microphysics scheme being far from perfect and the grid resolution of 4.5 km still being too coarse.

5. Concluding Remarks

[17] In this study, we have shown that the CMA/NMC operationally predicted heavy rainfall in the vicinity of Beijing is mostly caused by the topographical and frontal lifting of high-θ_e air, whereas in nature the topography and front accounted for the initiation and backbuilding of deep convection in the warm sector, and the final small portion of rainfall, respectively. It was the echo training of convective cells along a quasi-stationary linear MCS and subsequent rainfall enhancement by a deep layer of southerly moisture supply that were responsible for most of Beijing's extreme rainfall occurring in the warm sector. Thus, we conclude that the "right results" by the then operational NWP models were obtained for the above two wrong reasons.

[18] We have also shown that a high-resolution cloud-permitting model could reproduce reasonably well the timing, distribution, and intensity of this extreme event, as well as certain storm-scale details and rainfall-production mechanisms. Since the echo-training process appears to occur in a large percentage of extreme rainfall events in China, the United States, and elsewhere, our results have important implications to the development of cloud-permitting NWP models and the general improvement of warm-season quantitative precipitation forecasts (QPFs), especially associated with the warm sector rainfall, as the grid resolution increases [*Lean et al*., 2008; *Zhang and Zhang*, 2012]. On the other hand, some other studies have indicated that going from coarse-resolution convective parameterization to fine-resolution cloud-permitting NWP models adds little value to the prediction of heavy rainfall [*Gallus*, 1999; *Kain et al*., 2008; *Schwartz et al*., 2009]. Thus, more case studies of extreme rainfall events occurring under various environmental conditions over different geographical locations should be conducted in the future to gain insight into various mesoscale processes taking places in the associated MCSs, and identify the relative importance of model initial conditions, physical parameterizations, and grid resolutions in determining the QPFs of these extreme events.

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