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Observation and modeling analyses of the macro- and microphysical characteristics of a heavy rain storm in Beijing

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ABSTRACT

Beijing and its surrounding areas experienced a heavy rain event from 21 to 22 July 2012. The event can be divided into two phases: a warm-sector precipitation phase, ahead of the cold front, and a cold front precipitation phase. Observational analyses indicated that this rain event resulted from the cooperation of upper- and lower-level weather systems, and also the development and merging of mesoscale convective storm clusters in cumulus-embedded stratus. Simulation results showed that water vapor and hydrometeors transported into Beijing came mainly from the west and south and then exited from the north and east in general. All hydrometeors except ice crystals showed net inflow during the warm-sector phase, while all hydrometeors showed net outflow during the cold front phase overall. The interactions between cold and warm cloud microphysical processes generated the severe precipitation, with melting of graupel into rainwater contributing the most. Cold cloud processes contributed more to rain in the cold front phase compared to that in the warm-sector phase. The general precipitation and hydrometeor precipitation efficiencies were 67.0% and 86.3% in the warm-sector phase, while those in the cold front phase were 44.0% and 74.6%, respectively.

1. Introduction

China is a country that experiences many rainstorms. There are different degrees of rainstorm-induced floods every year, which cause great human and economic losses (Tao, 1980). The occurrence of a heavy rainstorm is the result of interaction between different weather systems (Maddox et al., 1979; Tao, 1980). In large-scale terms, Ding et al. (1980) proposed three basic synoptic-scale circulation patterns leading to rainstorms in northern China: vortex, warm shear line, and low trough cold front. Moore et al. (2003) found that the heaviest rainfall regions were located at the northern edge of quasi-stationary fronts, through analyzing 21 warm-season precipitation cases in the central United States. Milrad et al. (2014) studied 1663 precipitation cases in Canada and classified 10% of the strongest ones into four types: cyclones and strong weather-scale quasigeostrophic uplift, warm front precipitation, cold front precipitation, and little synoptic or mesoscale quasigeostrophic uplift. Many studies have indicated that rainstorms are triggered by mesoscale convective systems (Cohuet et al., 2001; Moore et al., 2003; Schumacher and Johnson, 2005; Zhou, 2009; Mastrangelo et al., 2011; Riesco Martín et al., 2013), and some studies have even reported that rainstorms are affected by mesoscale convective vortices (Fritsch et al., 1994; Trier and Davis, 2002; Ullah and Gao, 2013). Meanwhile, research has also shown that topography plays a very important role in the formation of convective rainstorms. Rudari et al. (2004) pointed out that cyclonic convergence induced by topography is the key basis for storms. Tucker and Crook (2005) found that convective rainfall occurs more readily on the leeside of a mountain. The long axis of storms is usually parallel to the direction of wind on the leeside. Langhans et al. (2011) revealed that the intensity of

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one of the rainbands they studied was related to the location of the topography.

The advection of water vapor and different types of hydrometeors greatly affects formation of precipitation via cloud microphysical conversion processes. Zhou and Yu (2005) found that water vapor transportation is associated with summer rainfall anomalies, and the water vapor sources of normal and abnormal summer rainfall are different. Zhao et al. (2007) attributed the occurrence of an extraordinary rainstorm in Hong Kong to wet and warm airflows from the south. Milrad et al. (2009, 2010) found that the lengthy persistence of a rainstorm in Newfoundland was the result of water vapor transportation from the Gulf Coast of the United States and Atlantic Ocean.

Cloud microphysical processes are another important factor affecting rainstorms. Li et al. (2002a) employed a 2-D cloud model to simulate tropical sea convective systems in December 1992. They found that cloud droplets mainly came from condensation. Moreover, the cloud droplets were converted into rain by the aggregation of cloud water by ice, snow, and graupel in the layer beneath 0 °C level, or by collision-coalescence of cloud water by rain in the warm layer. Colle and Zeng (2004) simulated a rainfall event in Sierra Nevada on 2 February 1986 using the Reisner-2 scheme in MM5. The results showed that condensation, deposition into snow, and melting of graupel were the most important among the microphysical processes. Wang et al. (2007) analyzed the cloud microphysical structure and precipitation process during the breakout of the summer monsoon in southern China from May to June 1998. They concluded that ice-phase processes, including aggregation, were negligible in the mature stage but were very important in the dissipating stage. Evaporation, however, was insignificant in the whole precipitation process. Rowe et al. (2012) simulated the organized convection in the mountains of northwestern Mexico, and found that warm and cold cloud microphysical processes were all very important in the strong precipitation process.

Beijing and its surrounding areas suffered an extraordinary rainstorm from 1000 BST (Beijing Standard Time) 21 to 0400 BST 22 July 2012 (hereafter referred to as the "7.21" Beijing extraordinary rainstorm). Although there have been several extraordinary rainstorms in northern China in recent decades, such as the extraordinary rainstorm and flood in the Haihe River region in August 1963, the extraordinary rainstorm in Henan Province in August 1975, and the heavy rainstorm in Hebei Province in August 1996, the "7.21" Beijing extraordinary rainstorm event was the strongest in northern China since detailed meteorological records began in 1951 and also caused the greatest number of casualties and economic losses. Although there have been some studies of the "7.21" Beijing extraordinary rainstorm (e.g., Sun et al., 2013; Zhang et al., 2013), some questions are still unanswered, such as the water substance transportation, precipitation mechanism, and precipitation efficiency. As we all know, water substance transportation is very important to precipitation mechanism, and precipitation mechanism is the scientific base of rainfall forecast accuracy. At the same time, precipitation efficiency is an important indicator for knowing the distribution and conversion of the cloud water resources in the air. Therefore, in this paper, the transportation of water vapor and hydrometers, precipitation mechanism, and precipitation efficiency will be discussed for this heavy rainstorm. Various observational data, including National Centers for Environmental Prediction (NCEP) reanalysis data, satellite cloud charts and cloud-top temperature images, radar reflectivity maps, Meteorological Information Comprehensive Analysis and Process System (MICAPS) data, and Weather Research and Forecasting (WRF) model simulations, are used to analyze the "7.21" Beijing extraordinary rainstorm, with the aim of obtaining a clear understanding of the macro- and microphysical characteristics of this rainfall event.

2. Rainfall process

According to the observation, the rainband oriented in a southwest to northeast direction (Fig. 1a). The precipitation process can be divided into two phases. The first phase took place in warm sector, ahead of the cold front, from 1000 to 2000 BST 21 July. It was characterized by wide range, long-term maintenance and short-term strong rainfall. The second phase was in the cold front area and occurred from 2000 BST 21 July to 0400 BST 22 July (Sun et al., 2013). The location of the frontal surface on the ground at different times from 21 to 22 July is depicted in Fig. 1b.

Fig. 2a–c shows the observed hourly rainfall amounts from 0800 BST 21 to 0800 BST 22 July based on data from eight national meteorological observatories. Fangshan (FS), Mentougou (MT), and Shijingshan (SJ) are in the southwest; Fengtai (FT), Daxing (DX), and Chaoyang (CY) are in the south; and Miyun (MY) and Shunyi (SY) are in the northeast and east of Beijing (Fig. 1b). For the moving of the cold front, the southwest parts were in the region of the warm sector first, and it rained first there. Then with the moving of the cold front, the other parts were in warm sector and the time when the rain in the other parts began was later. At the same time, the lifting of the airflow from the southeast was blocked by the topography in the west and north of Beijing, and the accumulated rainfall amounts in the southwest parts were larger. In the cold front phase after 2000 BST 21 July, the rainfall amounts decreased obviously. Compared to the rainfall in the warm-sector phase, the level of inhomogeneity weakened in the cold front phase. Data analyses indicate that this rainstorm possessed clear regional characteristics with strong spatial and temporal inhomogeneity, which was due to the moving of the cold front and lifting of topography.

3. Large-scale circulation and stratification

The upper-air charts in Fig. 3 show that, at the 200 hPa level, Beijing was directly in the right-front of the exit region of the upper-level jet stream at 0800 BST 21 July (Fig. 3a). Then the upper-level jet stream axis moved eastward and strengthened. The upper-level jet stream had a strong pumping action on the convection in Beijing. At the 500 hPa level, Beijing was in front of a westerly trough. The trough moved very slowly (Fig. 3a–c) because it was blocked by the western Pacific subtropical high north of Shandong Peninsula in the east of Beijing (Sun et al., 2013). It formed a "high-in-the-east–low-in-the-west" style weather pattern. Under these weather conditions, cold air from north to south, strong and warm moist air from the southwest, and warm and moist air produced by the periphery of the western Pacific subtropical high, all merged together over