A case study of cold-season thundersnow in Beijing

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\textbf{ABSTRACT}

The characteristics of local thundersnow at fine spatiotemporal scale on 9 and 10 November 2009 in Beijing were analyzed, using wind profiler, microwave radiometer, automatic weather station, Doppler weather radar, and satellite data. Furthermore, the causes of winter convection are discussed. The results showed that it was reflex weather. The cause of the thunder and lightning was the elevated convection above the lower cold and dry air, and the trigger for convection was the short wave trough and convergence in the middle level. This thundersnow event developed from monsoon-like long-lasting water vapor transport at 850 hPa from the South China Sea along with strong instability of, and convergence in, the conveyor layer.

1. Introduction

In 2009, snowfall in northern China was considerably heavier than normal (Ren, Chen, and Zhang 2010). The traffic in Shijiazhuang — the capital city of Hebei Province — was jammed by heavy snow on 10 November 2009. Beforehand, on the morning of 9 November 2009, graupel, ice crystals and thundersnow were sequentially observed in Beijing, and during the night it thundered again in Beijing, with heavy snowfall. The average precipitation in the Beijing urban area was 7 mm by 0600 LST 10 November 2009, with Haidian weather station, which is in the west of the urban area, observing an 18.5-mm precipitation maximum. It is very unusual in Beijing for lightning to occur in the morning and at night on a winter’s day.

In the North China Plain region, heavy snow mainly relates to the reflex of cold air, which means there is high pressure in the east of Beijing and the low-level wind in Beijing is easterly. The water vapor originates from mid-level southwesterly airflow, and the lower dry cold air mass acts as a wedge (Zhang, Hou, and Zhang 2007; Li, Zhang, and Shi 2015; Liu and Li 1998). High unstable potential energy exists above the blizzard area, accompanying a very low-level easterly jet and midlevel southwesterly jet (Zhao 2007). The low-level jet is caused by frontogenesis, with secondary circulation of the front triggering blizzards over Huabei Plain (Zhou and Tan 2008; Sheng and Yang 2002; Su, Jiao, and Lyu, 2012). In the Yangtze river area, thundersnow has been found to accompany burst warming and humidification at 700 hPa, which means strong warm advection and severe weather originating in the strong ascending motion near 700 hPa where a potentially unstable layer exists (Wang and Bei 1992; Zhang et al. 2006; Huang et al. 2017; Wang and Bei 1992).

Trapp et al. (2001) carried out a multi-scale analysis of a blizzard in the United States using double-polarization radar and two Doppler radar, pointing out that the snow lightning was caused by elevated convective cells embedded in stratiform cloud. Maesaka et al. (2003) discussed the relationship between graupel concentration and lightning location in winter thunder clouds using double-polarization weather radar. Some studies (e.g. Wang et al. 2018) have also shown the impacts of aerosols on thunderstorms, which are not discussed in this study (Vinzani and Changnonjr 1981; Market, Halcomb, and Ebert 2001; Melick 2008; Melick et al. 2008; Pettegrew 2008; Pettegrew et al. 2009).
For the 2008 Olympic Games in Beijing, a mesoscale meteorological observation network was developed, including automatic weather stations, Doppler weather radar, wind profiler radars, and microwave radiometers. Also developed was an automatic nowcasting system for convective storms, a rapid update cycle (RUC) system, and a local analysis and processing system (LAPS). In the present work, we used these data, as well as synoptic and satellite image analysis, for a detailed analysis of the thundersnow that occurred on 9–10 November 2009 in Beijing. The images presented in this paper were produced by the Objective Analysis and Graphic System (National Key Laboratory for the Severe Storm Research, Peking University (LSSR)), software for general weather forecasting and Python.

2. Meteorological analysis and convection potential

Heavy snow occurred in Beijing accompanied by lightning from 2300 LST 9 November to the early hours of 10 November 2009. The urban-area snowfall was greater compared to that in the northern mountainous areas. By 0600 LST 10 November, the urban average snowfall was 7 mm, with the largest snowfall being 18.5 mm in Haidian district. Thundersnow also appeared at Changping, Pinggu, Shunyi, Miyun, and Huairou weather stations. Several solid precipitation types — graupel, ice pellets, freezing drizzle, and snow — were observed. This thundersnow event broke the record for the latest-occurring winter thunder (5 November 2003) in Beijing.

Abnormal weather is associated with an unusual climatic background. During 1–8 November 2009, the temperature of North China was warmer than normal by about 3°C–4°C. On the 850-hPa weather map (Figure 1(a)), low-latitude water vapor was transported to North China by persistent low-altitude southerly wind, as with the summer monsoon. The convergence zone at 850 hPa was located in Beijing. The sealevel pressure map (Figure 1(b)) shows an inverted trough near North China, and a relatively shallow trough at 500 hPa. Cold air from Lake Baikal has a strong influence over North China from the northeast, and this situation is called ‘East High’ reflux weather. The wind above 700 hPa was southwesterly, below was northeasterly, and the wind speed at 925 hPa was 9 ms⁻¹ at 2000 LST 9 November.

Figure 1(c) is a map of the 0°C height of the RUC model, from which it can be seen that the steep gradient was in southern Beijing, and there were contours tracked the mountains to the west. Cold air piled up on the easterly side of the mountains, with warm and moist air climbing uponto the cold wedge at 850–700 hPa and forming a near-saturated wet layer in the radiometer image (Figure 2). Note that in the Skew-T diagram at 2000 LST (Figure 1(d)) the temperature at 758 hPa was 1°C, the potential unstable layer thickness was 1 km, and the inversion layer’s top height was 2.4 km. Beijing LAPS shows there was a CAPE center of 30–40 J kg⁻¹ in the Beijing urban area at 0030 LST 10 November. In Beijing, the main cause of lightening was the elevated convection of warm and moist air above the low-lying cold air; the convergence zone at this height could release the unstable energy, making the updraft flow of the convection.

3. Analysis of the triggering of convection

Multi-channel microwave radiometer data provide profiles of temperature, humidity, and liquid water by receiving weak energy from the atmosphere and clouds. The microwave radiometer at Guanxiangtai station (GXT; 39.80°N, 116.46°E) in Beijing uses a digital neural network algorithm to retrieve profiles in real time, meaning it is not exactly a numerical retrieval method (Li et al. 1997). The temperature algorithm use seven frequency channels between 51 and 59 GHz; water vapor uses five channels between 22 and 30 GHz, mainly located in the absorption zone of oxygen and water vapor molecules.

From the time series of the microwave radiometer data on 9 November 2009, it can be seen that the relative humidity below the height of 2 km was very small, while continuously near-saturated between 2 and 4 km (Figure 2). It can also be seen that, during the daytime of 9 November, the ground temperature continuously decreased owing to the cold northeasterly wind. Whereas, at 0100 LST 10 November, there was a change in temperature, humidity, and liquid water above the inversion layer, with the liquid water reaching 1.6 gm⁻³ because of the convection-produced super-cooled water droplets. A hot temperature tower appeared above the inversion layer, which is typical of the latent heat release in convection. When snowfall began, the surface air was saturated because of the melting of snow. However, on the morning of 9 November, although sporadic graupel and snow was observed, the radiometer image showed no corresponding changes, indicating that there was no convection in the morning, with only a weak cold front passing.

At Haidian station, the blizzard’s center, a wind profile radar was working routinely. This radar emits electromagnetic waves (wavelength: 22 cm) into the air, and receives the scattering energy of atmospheric turbulent vortexes to track the motion of the wind. From the time series of theprofiler data, it was southwesterly wind over Haidian at 0900 LST 9 November, and the wind speed at the altitude of 540 m reaching 14 ms⁻¹. After 1000 LST and below 1 km, the wind changed to northeasterly. As the
wind direction turned anticlockwise to altitude, it indicated the presence of cold advection in the boundary layer. At 0800 LST, a narrow cloud band could be seen in the satellite image, and several weather stations observed thunder and several solid precipitation types successively: graupel, ice pellets, freezing drizzle, and snow. Since there was no fluctuation in the microwave radiometer image, it was only a short-lived and weak precipitation occurrence.

It can be seen that a shallow trough passed through Haidian from 1600 to 1700 LST at the height of 1740–3000 m (Figure 3). At 1800 LST, the relative humidity over Haidian dropped from 90% to 67%, indicating another cold air front reached the area; the northeasterly wind altitude had risen to 2300 m and the wind speed was 10 m s\(^{-1}\) in 1000 m, but no convection had yet happened. At 2300 LST 9 November, further small fluctuations could be seen in the wind profiler above 2500 m, simulating the convection of the instable layer. The thundersnow began at 0000 LST. Between 0000 and 0100 LST, the precipitation of Haidian was 2 mm, and between 0100 and 0200 LST the snowfall quickly increased to 8 mm. The snowfall stopped at 0400 LST, and the total precipitation was 18.5 mm.

The mechanism of wind field variation observed by the wind profiler radar can be explained by existing theory. From the viewpoint of kinetic frontogenesis, there was an interaction between the temperature field and the flow field. At 0900 LST 9 November, cold air began to pass through the station, and in order to maintain the heat and
wind field balance the vertical wind shear was bound to increase. Secondary circulation of the front was forced out too. Similarly, after 2000 LST, the northeasterly wind speed at around 1000 m increased again, due to new cold air moving close to the station.

Because the potential instability layer lay above the inverse layer, the near-ground cold advection was therefore not the factor that stimulated convection; rather, it must have been the higher wind convergence. When convection started, the atmosphere quickly reached a stable state because of the lack of warm and wet air supply from the bottom. The sounding at GXT station the next morning (0800 LST 10 November) showed that the inversion layer was not destroyed, the northeasterly wind was enhanced, and thus on the final night there was short-lived elevated convection above the inversion layer.

4. Satellite and radar image analysis

Satellite images show that there were two mesoscale frontogeneses over Beijing. The first was on the morning of 9 November 2009 (0500 to 0800 LST), and it can be seen that a narrow quasi-east–west cloud band in Beijing was generated rapidly, moving eastward. This cloud band produced graupel, ice pellets, snowfall, and lightning, and it moved out of Beijing after 0900 LST.

Figure 4(a) shows that the second cloud band was generated in the evening to the west of Beijing, developing into a waveshape at 2300 LST while moving eastwards. The scale of the wave-shaped cloud band was about 115 km (north–south) by 657 km (west–east), with convective cells that had very low cloud-top temperature and that made thunder and heavy snow in Beijing at 0000 LST 10 November 2009.

The Doppler weather radar (CINRAD-98D; wavelength: 10 cm) was located in the southern suburbs of Beijing. The radial velocity map of the Doppler radar data showed the maintenance of southwesterly wind at high altitude and northeasterly winds at low altitude on 9 November 2009. Just before the heavy snow, the wind speed was significantly faster than earlier. A ‘bull’s eye’ pattern appeared on the radial velocity map at 2359 LST 10 November (Figure 4(b)), with the lower northeasterly wind speed reaching 10 m s\(^{-1}\), indicating the development of secondary circulation in the frontal zone that eventually led to heavy snowfall.

Radar echo animation showed that for the echo moving from west to east and slightly northward, the maximum echo intensity was 35 dBZ at 0000 LST 10 November, and the average echo intensity was 20 dBZ (Figure 4(c)). Since the scattering of ice crystals is much weaker than that of water droplets, the 20-dBZ
echo intensity indicated that the strong-echo area may have had both solid and liquid droplets. The sounding at GXT at 2000 LST 9 November showed that at 758 hPa the temperature was 1°C, and that water droplets possibly existed at the top of the inverse layer. A cross section of the volume scan data showed an echo mainly above 1.5 km, an echo top up to 10 km, and a strong echo center at the height of 5 km. Therefore, it can be inferred that the heavy snowfall was due to the upward movement of the southwesterly flow above the inversion layer with the release of unstable energy.

From the analysis of the satellite and radar data on 9 November 2009, there were two precipitation processes with different intensities, in the morning and at night. Since the Doppler weather radar wind field retains the same structure during the day, just the wind speed has pulsation, it is clear that both precipitation processes were due to two mesoscale frontogeneses caused by two cold-air fronts, and the second snowfall had significant convection.

Doppler weather radar, wind profiler radar and microwave radiometer data all have advantages and disadvantages in mesoscale meteorological analyses. They use different electromagnetic waves and constructions. For example, microwave radiometers use a neural network algorithm, which needs many iterations to train; Doppler weather radar cannot observe very high wind speeds and directions, whilst a wind profile radar can. However, wind profile radar data may be contaminated by rain.

5. Conclusion

Before the thundersnow event analyzed in this work, warm and moist southwesterly airflow delivered sufficient water vapor to Beijing. Owing to the 'Beijing Bay' terrain, the reflux made the warm and moist air flow above a deep inversion layer.

Satellite images show that there were two mesoscale frontogeneses, with the second stronger than the first. There was elevated convection in the second frontal zone, and the convection energy came from the potential instability of the conveyor layer above the inversion layer.

Figure 3. Wind profiler observation at Haidian station, from 0800 LST 9 November to 0200 LST 10 November.
The convection trigger was the rising motion of the mid-level shortwave trough and the convergence at 850 hPa or 700 hPa. The convection significantly enhanced the precipitation efficiency.

From the physical process of cloud electricity, thunderclouds must have different particles and an organized up-and-down flow (Sun et al. 2007; Takahashi et al. 2017; Becker, 2009; Kitagawa and Michimoto, 1994). Winter thunder must have a deep inversion layer and preferably have a near 0°C wet layer, as in this case. Thunder convection occurs rarely in the cold season because water vapor is less abundant in winter, meaning convection is weaker and shorter in duration. For convection in the warm season, if a low-level jet occurs, there is always torrential rain, and if accompanied by a cold front it will always be a squall line. Winter convection occurs only occasionally in part of the frontal zone. In the United States, the polar vortex can produce blizzards and a greater chance of thundersnow in places near the coast or around the Great Lakes (Crowe et al. 2006; Halcomb and Market 2010). In North China, moisture transport can come from the Bohai Sea, which is called reflux weather, or from the South China Sea by continuous airflow at 850 hPa, which is called the water vapor conveyor belt. In this case, the conveyor belt lasted a few days, accumulated enough unstable energy in Beijing, and then the convergence at 850 hPa or 700 hPa finally triggered the convection. Against the background of global warming, a weakening of the East Asian winter monsoon might increase the moisture transport to Northeast China, and thus there could be a snowfall increase too (Wang and He 2013; Moore, Renfrew, and Pickart 2008).

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References
Becker, A. E. 2009. “A Study of Lightning Flashes Attending Periods of Banded Snowfall.” Geophysical Research Letters 3636: 276–284. doi:10.1029/2008GL036317.
