Evolution and Development Mechanisms of a Rare Strong Arc-Shaped Squall Line Occurring in Northern Beijing in 2017

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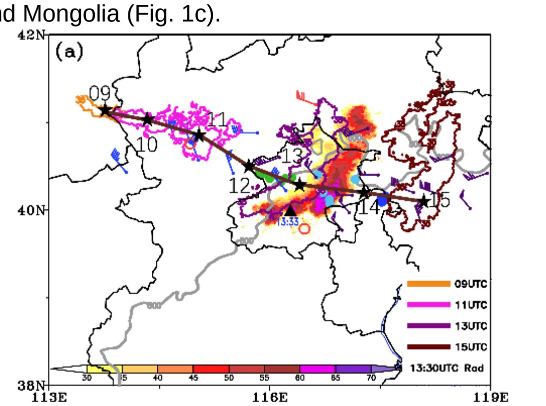
1. INTRODUCTION

Based on NCEP (National Centers of Environmental Prediction) analyses data and various observations from automatic weather stations, cloud-to-ground lightning positioning system, stationary meteorological satellites, and weather radars, this paper uses "ingredient-based method" to have comprehensively analyzed environmental conditions, evolution characteristics, trigger and development mechanisms of a rare strong arc-shaped squall line with maximum wind gust of nearly Beaufort Scale 12 and large hail, which swept the northwestern Hebei Province and central and northern Beijing during the period from afternoon to midnight of 7 July, 2017.

2. SEVERE CONVECTIVE WEATHER AND SYNOPTIC SITUATION

The strong arc-shaped squall line lasted for at least 7 hours, producing widespread severe convective weather in North China (Fig. 1a). The observed maximum wind gust reached 32.2 m/s. The evolution of cloud-to-ground lightning (Fig. 1b) shows that the number of lightning increased significantly during 10–12 UTC, the lightning was mainly positive at 11 UTC, and the proportion of positive lightning to total over the squall-line affecting area (38–42 °N, 113–119 °E) was greater than 40% (Fig. 1b), and what is more, it was close to 90% in most of the lifetime of the squall line.

The squall line occurred in the southwest side of a 500-hPa cold vortex. There were significant cold advection, significant upper-level and low-level jets, and significant low pressure at the surface. The cold vortex affected mainly North China, Northeast China, and Mongolia (Fig. 1c).



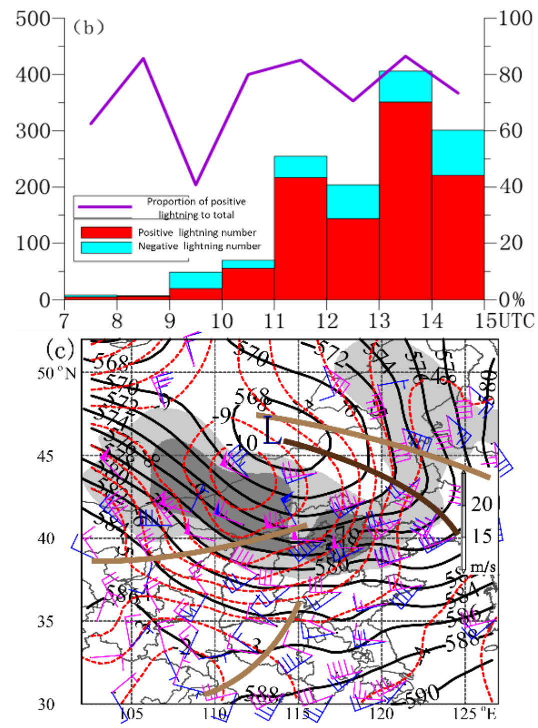


Fig. 1 Convective weather, the path of the squall line, cloud-to-ground lighting and synoptic situation (a) Convective weather and squall line path during 09-15 UTC July 07 (Different colorful dots represent hourly precipitation of no less than 20 mm; red circles represent sounding stations at Zhangjiakou and Beijing, respectively; black triangles present hail; gray solid line is contour of terrain height at 500 m; solid line which has black pentagrams on it is the path of the core of the strongest reflectivity of the squall line, 35 dBZ radar reflectivity contours are marked by colorful solid lines; the numbers are UTC every hour); shaded area represents 13:30 UTC radar reflectivity of no less than 30 dBZ; (b) Hourly cloud-to-ground lighting (38–42°N, 113–119°E) for 08-15 UTC July 07 (Blue bars represent negative cloud-to-ground lighting, red bars positive cloud-to-ground lighting, and polyline the proportion of positive cloud-to-ground lighting to total); (c) Synoptic situation at 12 UTC July 07 (Black solid lines are contours of geopotential height at 500 hPa, unit dagpm and interval 2 dagpm; red dotted lines are contours of temperature at 500 hPa, unit °C and interval 1 °C; gray shaded areas are wind speeds at 500 hPa; purple barbs are for 500 hPa; blue barbs are for 850 hPa; light brown solid lines are shear lines at 850 hPa; dark brown solid line is trough line at 500 hPa)

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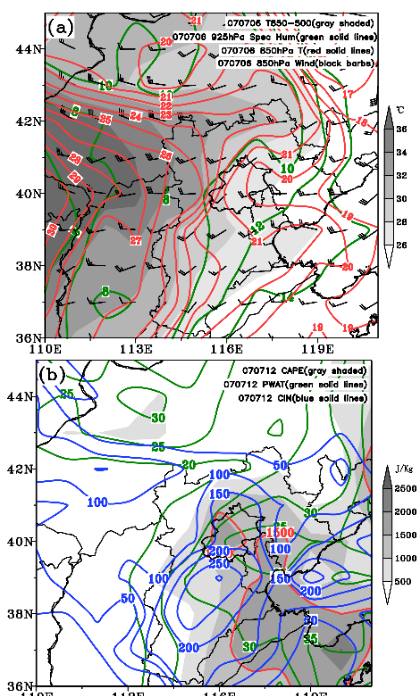
3. ENVIROMENTAL CONDITIONS

Strong low-level jet, larger convective available potential energy (CAPE) above 2000 J/kg, intense 0–6 km and 0–3 km vertical wind shear were very favorable for the development and maintenance of the squall line and a supercell storm embedded in the squall line, which produced large hail and high winds. Level of the wet bulb temperature 0 °C at 3.8 km altitude was in favor of producing large hail. Dewpoint deficit of the middle troposphere up to 30 °C and larger vertical temperature lapse rate caused larger downdraft convective available potential energy (DCAPE), which favored very much bow echoes and convectively driven high winds.

4. TRIGGER MECHANISM

The convection initiation of the squall line was triggered near a surface convergence line between northwesterly winds and southwesterly winds. At 05-08 UTC, a surface convergence line between the northwesterlies and southwesterlies was maintained in the convective area, both of which had high wind speed up to about 8 m/s. The initiated convective system formed near the convergence line. At 05 UTC, cumulus lines were seen in the visible image of FY-2G geostationary meteorological satellite; at 08 UTC, the brightness temperature of blackbody (TBB) of the convection was lower than -32 ℃ (not shown in the figure). As the convergence line was maintained relatively stable in the region, and there was new convection development, at about 09 UTC, the convection developed into a nearly east-west linear convective system which was basically consistent with the convergence line.



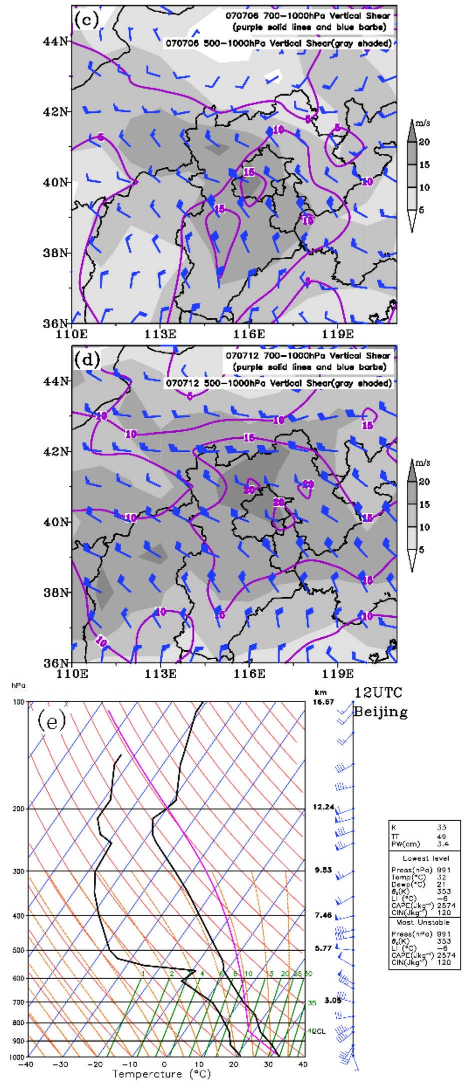


Fig. 2 Environmental conditions for the squall line (a) Temperature and humidity at low level for 06 UTC July 07 (Gray levels show temperature difference from 850 hPa to 500 hPa, unit is °C; green solid lines are contours of specific humidity at 925 hPa, unit is g/kg; black barbs are for 850 hPa; red solid lines are contours of temperature at 850 hPa, unit is °C and interval 1 °C); (b) Convective instability energy and moisture (Gray shaded areas represent CAPE, unit is J/kg and interval 500 J/kg, and red solid lines are contours of 1500 J/kg; blue solid lines are contours of CIN, unit is J/kg and interval 50 J/kg; green solid lines are contours of precipitable water content, unit is mm, interval is 5 mm); (c) and (d) are vertical shears for 06 UTC and 12 UTC respectively (Purple solid lines are contours of vertical shear from 700 hPa to 1000 hPa, blue barbs are for vertical shear wind from 700 hPa to 1000 hPa, unit is m/s, interval is 5 m/s; gray shaded areas represent vertical shear from 500 hPa to 1000 hPa, unit is m/s); (e) Skew T-log p diagram at Beijing sounding station (Thick magenta solid line is the lifting curve, thick black solid line on the right denotes temperature profile and thick black solid line on the left represents dewpoint profile. Note that the wind

triangle represents 20 m/s, the full barb 4 m/s, and the half barb 2 m/s.)

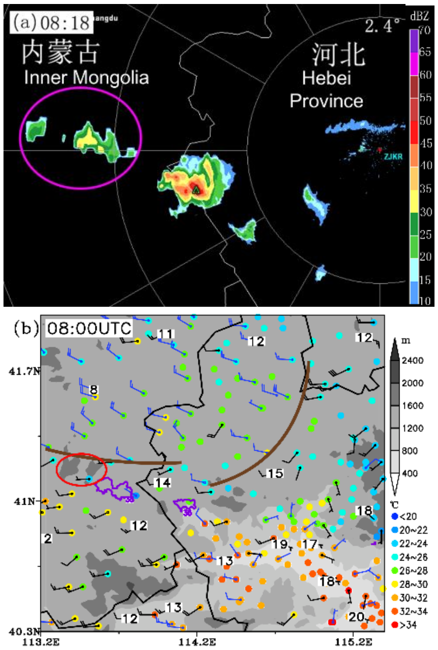
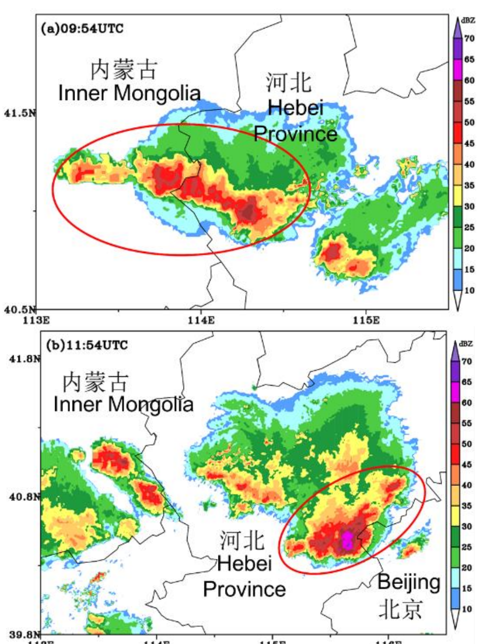


Fig. 3 Radar reflectivity of 2.4° elevation at Zhangjiakou radar station for 08:18 UTC July 07, 2017 (a) and observations from automatic weather stations (AWS) for 08:00 UTC (b)

(a) Magenta ellipse denotes the location of the initial convective system; (b) Different colorful dots denote temperature, gray levels show terrain height, numbers represent dewpoint temperature, blue barbs denote northerly winds, black barbs denote southerly winds, purple solid lines are contours of 35 dBZ radar reflectivity, brown solid lines are contours of surface convergence line, and red ellipse denotes the location of the initial convective system)



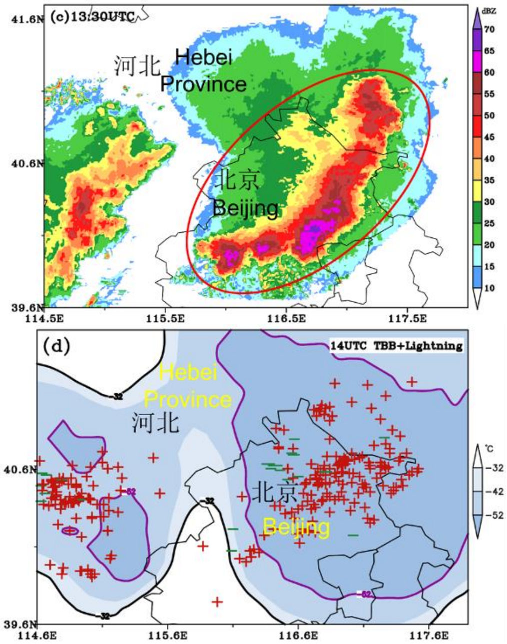


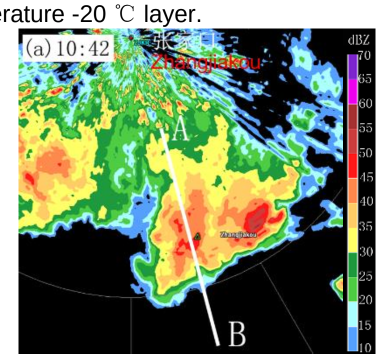
Fig. 4 Radar reflectivity no less than 10 dBZ (a, b, c; red ellipses denote the location of the convective system at different period), TBB of FY2G and lightning. (a) 09:54 UTC; (b) 11:54 UTC; (c) 13:30 UTC; (d) TBB of FY2G at 14 UTC and lightning for 13-14 UTC (shaded areas represent TBB, unit is °C; black solid lines are contours of -32 °C, purple solid lines are contours of -52 °C)

5. EVOLUTION AND MECHANISM

Radar observations show that the squall line developed from a linear convection system to a cluster supercell storm, and finally to an arc-shaped squall line with significant overhang echoes, weak echo regions, mesocyclone (or mesovortex), and strong rear inflows which caused rear inflow notches.

At 09 and 10 UTC in the early stage of the squall line, the radar maximum reflectivity was greater than 55 dBZ, and its vertical structure shows that the core of strong reflectivity factor was high with a certain overhang structure.

At 11:48 and 11:54 UTC, the convective system moved eastward to the vicinity of Guanting Reservoir in Huailai, Hebei Province, the strongest reflectivity observed by Beijing Daxing S-band radar (Figures 6a and b) exceeded 60 dBZ, and the 50 dBZ reflectivity rose to a height of nearly 12 km, far exceeding 7.5 km of temperature -20 ℃ layer.



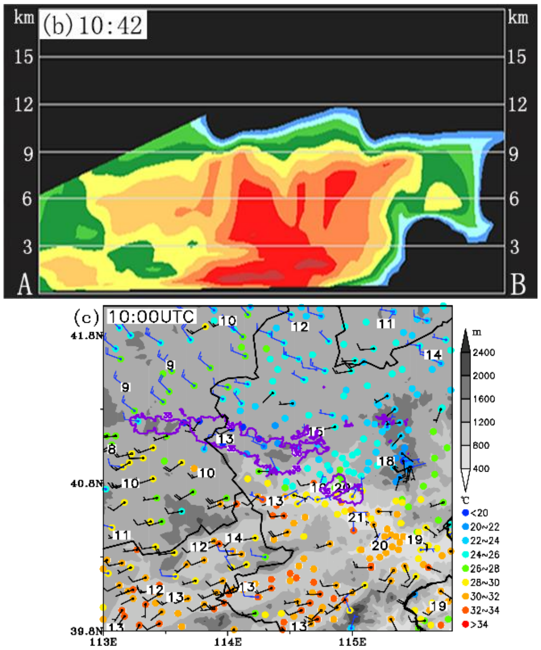
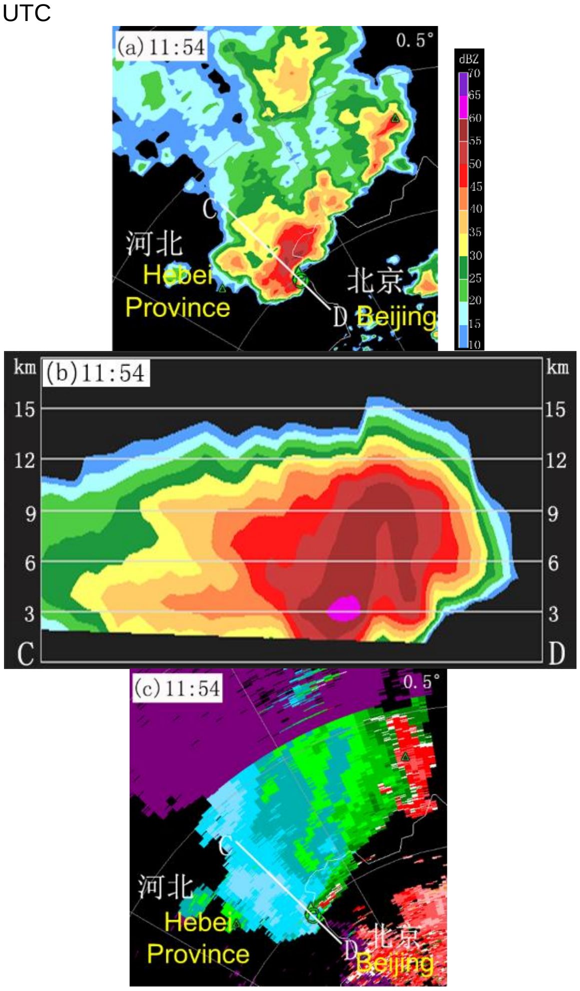


Fig. 5 Radar reflectivity at Zhangjiakou radar station for 10:42 UTC and observations from AWS for 10:00 UTC July 07, 2017. (a) reflectivity at 0.5° elevation; (b) is vertical cross section along white solid line (AB) in Fig a; (unit is dBZ; the numbers on the ordinates of (b) are altitude, unit is km); (c) same as Fig. 3b, but for 10 UTC



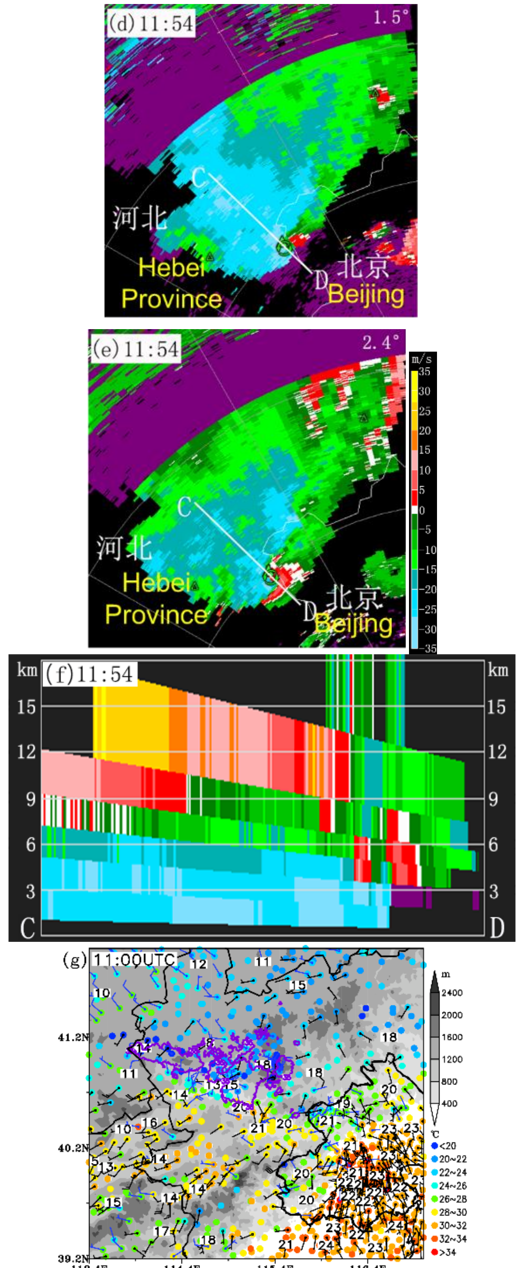
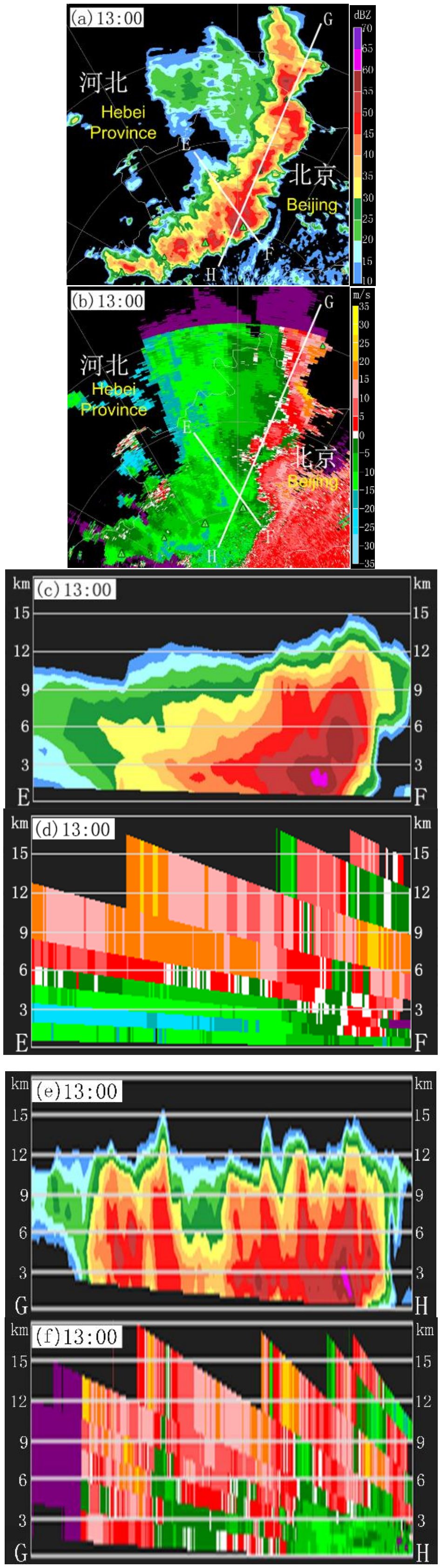


Fig. 6 Radar reflectivity and radial velocity at Beijing radar station for 11:54 UTC and observations from AWS for 11:00 UTC July 07, 2017. (a) radar reflectivity at 0.5° elevation; (b) is vertical cross section along solid line (CD) in Fig. a ; (c), (d), (e) and (f) are distributions of radial velocity at 0.5°、1.5°、2.4° respectively (In a and b, unit is dBZ; in c, d, e and f, unit is m/s); (g) is same as Fig.3b, but for 11:00 UTC

With the movement of the supercell storm to Yanqing of Beijing, the outflow northwest wind generated by the supercell, the surface southwest wind and the southeast wind near the Beijing area formed significant convergence and uplift. In addition, because of the favorable water vapor, larger CAPE and vertical wind shear conditions, at 12:18 UTC, the original scattered convective storms formed a



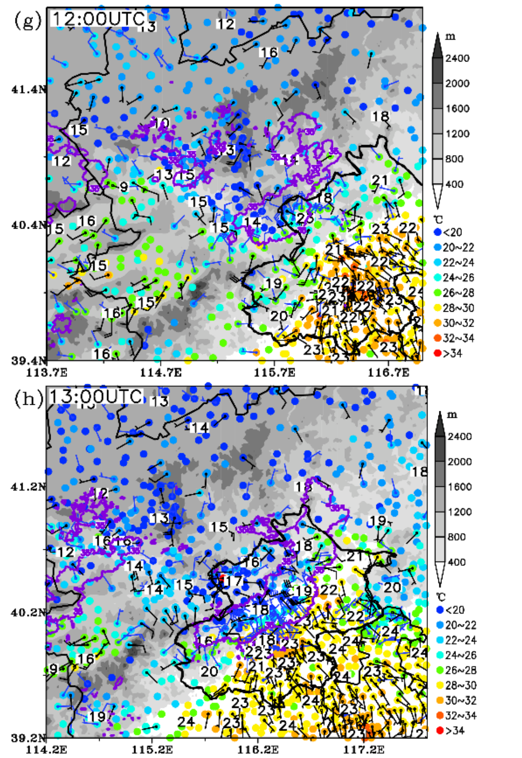


Fig. 7 Radar reflectivity and radial velocity at Beijing radar station for 13:30 UTC and observations from AWS for 12:00 and13:00 UTC July 07, 2017

(a) and (b) are for 0.5° elevation; (c) and (d) are vertical cross sections along white solid line (EF) of (a); (e) and (f) are vertical cross sections along white solid line (GH) of (a); (a) radar reflectivity; (c) radial velocity (In (a), (c) and (e), unit is dBZ; in (b), (d) and (f), unit is m/s; (g) and (h) are same as Fig.3b, but for12 UTC and 13 UTC respectively

northeast-southwest "bow" squall line system with bow echo characteristics and obvious wave shape, in which the supercell was embedded.

The supercell storm prior to the formation of strong bow squall line had obvious hook echo characteristics. The supercell and the mature squall line had significant overhang echo, weak echo region, mesocyclone (mesovortex in the later stage of squall line maturity), intense rear inflow and rear inflow gap. Intense downdraft induced by strong jet in the middle of troposphere and high dewpoint deficit was the main cause for the formation of the bow echoes in the squall line. The mechanisms of maintaining the squall line and bow echoes include: large CAPE and DCAPE, and intense vertical wind shear.

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