Observations of a Heavy Rainfall Event in Shanghai on 5 August 2001

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Abstract

An extremely heavy rainfall event was observed in Shanghai on 5 August 2001. It had the maximum 24-h accumulated precipitation of 275.2 mm and caused serious floods. This paper documents the detailed evolution of this event by using a suite of observational data, including Geostationary Meteorological Satellite (GMS)-5 satellite images, Weather Surveillance Radar 88 Doppler (WSR-88D) radar data, automatic rain-gauge and sounding data, and objective reanalysis.

The synoptic situation prior to the heavy rainfall was characterized with a north-south oriented trough at 500 hPa and a surface meso-scale low with a surface cyclonical circulation at 00 UTC 5 August 2001. A lower-level southerly jet on the eastern flank of this meso-scale low supplied humid air to fuel the heavy rainfall. The soundings indicated that the atmosphere was most unstable before and during the rainfall, with large convective available potential energy. The clockwise rotation of wind direction with height suggested the warm advection over Shanghai. WSR-88D radar reflectivity of convective systems exceeding 50 dBZ, with large vertical integrated liquid value of 23–32 kg m$^{-2}$, suggested that rainfall was very intense.

1. Introduction

Heavy rainfall events, disastrous weather phenomena that cause floods and mudslides, have received considerable attention from the research community during the past decades. It has been shown that most of heavy rainfall events are associated with meso-scale convective systems (Tao et al. 1980; Ogura 1991; Peng and Tsuboki 1997; Kato and Goda 2001). Despite some basic understanding of heavy rainfall that has been gained from previous studies, further investigations of these events are very important because of their serious threats to human lives and properties, and difficulty in prediction.

Tao et al. (1980) investigated heavy rainfall
events in China systematically. Their study (pp. 10–11) indicated that persistent synoptic conditions, a continuous supply of water vapor, the release and regeneration of the CAPE (Convective Available Potential Energy) are necessary conditions for maintaining heavy rainfall. They classified heavy rainfall events into three categories based on 24-h accumulated precipitation: 50 mm ≤ heavy ≤ 100 mm, 100 mm ≤ severely heavy ≤ 200 mm, and extremely heavy > 200 mm. Due to the great geographical variations in China, this definition of heavy rainfall varies from one region to another.

An extremely heavy rainfall event accompanied by convective systems was observed in Shanghai on 5 August 2001. Torrential precipitation resulted in severe floods that affected over 10,000 families in Shanghai (Shao and Huang 2002). This is a rare event, setting the record for 24-h accumulated rainfall of 328.9 mm\(^1\). The maximum hourly rain rate was over 90 mm\(\text{h}^{-1}\) in Shanghai since official meteorological observations began in 1873 year. This case is obviously falling into the extremely heavy rainfall classification of Tao et al. (1980). This heavy rainfall event was the subject of a number of studies published in Chinese journals (Cao 2002; Chen 2002; Qi 2002; Yao 2002), but its characteristic features and detailed evolution have not been described in a comprehensive manner, because of limited data sources these studies used.

The purpose of this paper is to study the characteristic features of this extremely heavy rainfall event by using all available observational data, including Geostationary Meteorology Satellite (GMS)-5 satellite data, Weather Surveillance Radar 88 Doppler (WSR-88D) radar data, automatic rain-gauge and sounding data of Shanghai. The rest of the paper is organized as follows. Data sources and methodology are introduced in Section 2. Analysis results are presented in Section 3. Sections 4 and 5 offer further discussion and summary respectively.

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1 The accumulated precipitation of Xujiahui station of Shanghai from 00 UTC 5 to 00 UTC 6 August 2001 was 275.2 mm. Also there was another report with the maximum precipitation of 328.9 mm at the port of Huangpu River that crossed the central part of Shanghai city.
GMS-5 infrared imagery, from 00 UTC 05 to 00 UTC 06 August 2001, were downloaded from the website of http://weather.is.kochi-u.ac.jp. Upper and surface station data during the same period were supplied by the Chinese Meteorology Agency (CMA). Objective Analysis Data (OAD) were constructed by using the 1° × 1° aviation data of National Center for Environment Prediction (NCEP) as the first guess fields, and interpolating the station observation data on a 0.5° × 0.5° grid following the Cressman objective analysis method. In addition, WSR-88D radar imagery, the sounding data at station 58362 of Shanghai and precipitation observations by automatic rain-gauge stations were employed in the investigation (Fig. 1).

3. Analysis results

Figure 2 shows the hourly-accumulated rainfall observed at 99113 station of Shanghai. The rainfall started at 10 UTC 05 August 2001 and lasted until 10 UTC the next day. Two precipitation peaks, with intensity exceeding 28 mm h⁻¹, were found around 17 UTC 05 and 10 UTC 06 August 2001, respectively.

3.1 Synoptic overview

Synoptic situations prior to the heavy rainfall were analyzed based upon OAD data. At 00 UTC 05 August 2001, an unusually deep trough extended from north to south along 118°E over the west of Shanghai (Fig. 3a). Associated with this trough, a cold airmass characterized by −3°C isotherm existed over eastern China. Under this upper-level trough, there was a closed meso-scale low characterized by 1010 hPa, existed at the surface around (32°N, 117°E) immediately to the northeast of Shanghai (Fig.

2 There are totally 41 automatic rain-gauge stations in Shanghai. Due to communication problems, 23 station data, most of them located in the urban area of Shanghai, were unavailable on August 5, 2001.

3 The hourly rainfall was accumulated between the previous 00 min and the present 00 min.
3b). Associated with this surface meso-scale low is a strong southerly jet with speed of about 10 ms$^{-1}$, which transports humid air from the south. As the time elapsed, the upper-level trough, the cold airmass, and the surface low remain nearly unchanged in their geographical locations (not shown). Such stable synoptic situations are favorable for heavy rainfall (Tao et al. 1980).

Figure 4 shows the distributions of other variables at 00 UTC 5 August 2001, based on OAD. At 700 hPa (Fig. 4a), there existed a strong southerly jet, with maximum speed of 16 ms$^{-1}$. This Lower-Level Southerly Jet (LLSJ) passed over Shanghai. At 850 hPa there was a NNW-SSE oriented humid belt (humidity is 17–18 g kg$^{-1}$) over Shanghai (Fig. 4b). Thus humid air was advected by this jet from the south. The maximum value of horizontal advection of specific humidity $-\mathbf{v} \cdot \nabla q$, reached to $12 \times 10^{-8}$ kg kg$^{-1}$ s$^{-1}$ at 850 hPa (see Fig. 4c). The advection by LLSJ provided continuous humid air supplies, which led to a convergence of moisture flux $\mathbf{V} \cdot (q\mathbf{V})$ at 850 hPa, about $-3.0 \times 10^{-4}$ kg kg$^{-1}$ s$^{-1}$ near Shanghai (not shown), to fuel the heavy rainfall that followed. At 850 hPa (Fig. 4d) positive relative vorticity, associated with the upper-trough/surface low, amounted to $9.0 \times 10^{-5}$ s$^{-1}$.

3.2 Satellite observations

Figure 5 shows the evolution of cloud systems based on GMS-5 satellite imagery between 00 UTC 05 to 00 UTC 06 August 2001. At 00 UTC 05 (Fig. 5a), a meso-scale cloud system was found about 100 km southwest of
Fig. 5. GMS-5 satellite images from 00 UTC 05 to 00 UTC 06 August 2001 showing detailed evolution of meso-scale cloud systems “A” and “B”.
Shanghai. Here we name this cloud system as “A”. During the first three hours of August 5 (Fig. 5b), cloud system “A” experienced no significant change and kept its original shape and location. From 03 to 06 UTC (Fig. 5c), cloud area of “A” increased significantly, suggesting that cloud system “A” developed quickly during that time. At 08 UTC (Fig. 5d), another mesoscale cloud system “B” formed about 150 km southwest of “A”. Convective features of cloud systems “A” and “B” were distinct during this period of time, because they were very bright at that time.

From 08 to 10 UTC (Fig. 5e), clouds “A” and “B” developed quickly as reflected by their increasing brightness on satellite images. At 12 UTC (Fig. 5f), cloud “A” dissipated gradually, but cloud “B” still kept developing, increasing its area and brightness. Around 14 UTC (Fig. 5g), cloud “A” was no longer identifiable, but “B” still persisted, in spite of a decrease in its brightness. Cloud “B” appeared to be weakening at 16 UTC (Fig. 5h), but moved over Shanghai and developed again into a tightened circular system at 18 UTC (Fig. 5i). At 00 UTC 06 (Fig. 5j), “B” moved slightly eastward offshore, maintaining the well-organized circular shape.

3.3 Surface observations

Figure 6 depicts the surface weather observations before and during the heavy rainfall. From the morning to the evening of 05 August 2001, Shanghai and its neighbors were covered

![Fig. 6. Surface weather observations: (a) 00 UTC, (b) 06 UTC, (c) 12 UTC, and (d) 18 UTC 05 August 2001. The dark shade within the circle represents the cloud amount at a given observation station; the numeral to the upper-left represents air temperature (°C); a full barb represents a wind speed of 5 ms⁻¹, and a half barb 2.5 ms⁻¹.](image-url)
by dark clouds. In the morning around 00 UTC (00 UTC = 08 Beijing Standard Time), air temperature of Shanghai reached to 30°C with weak southerlies (Fig. 6a). The surface wind fields suggest the formation of a cyclonically circulating in accordance with the surface meso-scale low system (Fig. 3b). In the afternoon around 06 UTC (Fig. 6b), air temperature of Shanghai was about 33°C, and the surface wind field still maintained the cyclonically circulation. As time elapsed, rainfall seemed to start from the west of Shanghai, and the surface cyclonically circulation dissipated gradually (Figs. 6c,d).

3.4 Vertical sounding

The thermodynamic structure of the environment, before and during the heavy rainfall event, can be deduced from vertical soundings at station 58362 (31.41°N, 121.46°E) located just north of Shanghai's urban area. Figure 7 shows temperature and dew-point over Shanghai as a function of pressure at 00 UTC and 12 UTC 05 August 2001. The most important feature before the heavy rainfall was the unstable stratification of the atmosphere (Fig. 7a). At the surface the pressure was 1010 hPa, the temperature was 29°C, the dew-point was 25°C, and the equivalent potential temperature was 359 K. The lifting condensation level was at about 950 hPa, and the level of free convection was at 900 hPa. The atmosphere was very unstable, with a CAPE of 2209 J kg⁻¹. Winds turned gradually from southeasterly below 400 hPa to westerly above 300 hPa. This clockwise rotation of wind direction with height suggests a warm advection over Shanghai, which led to the further accumulation of atmospheric instability.

During the heavy rainfall the environment conditions remained nearly the same at 12 UTC (Fig. 7b). At the surface, pressure decreased to 1006 hPa, temperature to 27°C, dew-point was 26°C, and equivalent potential temperature was 358 K. Thus the atmosphere was still unstable, with a CAPE of 1633 J kg⁻¹. Below 500 hPa the southeasterlies dominated, and above 400 hPa the winds turned to westerly. The southeasterlies below 500 hPa advected the warm and humid air from the south, fueling the rainfall in the cloud system over Shanghai.

3.5 Radar and rain-gauge observations

WSR-88D is an advanced next-generation weather radar, widely used in detecting and monitoring severe weather events that threaten life and property. Its use ranges from the early detection of damaging winds to estimating rainfall amounts. WSR-88D radar of Shanghai is located in (31.001°N, 121.885°E) at
an elevation of 44.2 m above the mean sea level (see its position in Fig. 1). Its maximum detection range is 230 km (124 nautical miles). The appendix lists some important specifications of this radar.

Around noon (04 UTC) of 5 August, heavy rainfalls started to occur in Suzhou and Wuxi, west of Shanghai. It was not until 07 UTC that Shanghai began to be influenced by the rain band. After 07 UTC, the echo of convective cell started to appear in the western edge of the Shanghai radar. The sequence of radar reflectivity maps clearly showed convective cells with reflectivity exceeding 40 dBZ (not shown), a threshold for convective rainfall (Pradier et al. 2002). As time elapsed, a spiral-shaped rain band approached Shanghai accompanied by heavy precipitation. At 1632 UTC (Fig. 8a), radar reflectivity indicates a SW-NE oriented echo band exceeding 50 dBZ west of Shanghai, suggesting that rainfall was heavy at that time.

The WSR-88D radar can also measure wind direction and speed at various atmospheric levels. Figure 8b depicts the vertical wind profiles from 1524 to 1622 UTC 5 August 2001. The southeasterly prevailed at lower levels, while southwesterly-westerly winds dominated at upper levels. Strong vertical wind shear, with a clockwise rotation of wind direction with height, is not only indicative of warm advection, but is also crucial for storm organization and intensity, because larger shear storms typically produced more precipitation, as they were processing water vapor at a faster rate (Phillips 1973; Fovell and Ogura 1989).

Figure 8c displays Vertical Integrated Liquid (VIL) content measured by the WSR-88D radar at 1632 UTC 05 August 2001. There was a NE-SW oriented rain band, with a maximum value of 27 kg m$^{-2}$ taking place 55 km west of

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4 Unfortunately, WSR-88D radar stopped acquiring data from 1635 to 1935 UTC 5 August 2001.
Shanghai. From 1331 to 1632 UTC, three peaks of VIL with heavy rain rates 24, 30, 32 kg m\(^{-2}\) were found by WSR-88D radar observations at 1453, 1533 and 1602 UTC, respectively (see Fig. 9).

Figure 10 presents the time-distance cross-section of hourly-accumulated precipitation, based on 10 automatic rain-gauge stations that oriented nearly in the N-S direction. Three precipitation peaks were observed around 17 UTC, 24 UTC 05 and 11 UTC 06 August, respectively, suggesting the passage of several convective cloud systems over Shanghai. The main precipitation event occurred from 13 UTC to 19 UTC 5 August 2001. The maximum hourly precipitation amounted to 90 mm h\(^{-1}\), taking place around 17 UTC at station 99105. These automatic rain-gauge observational data are very consistent with the radar observations.

4. Discussion

As far as we know, forecasters of Shanghai Central Meteorological Station have published several short notes in Chinese on several aspects of this heavy rainfall event based on limited data sources (e.g., Cao 2002; Chen 2002). This section discusses, in the context of these previous studies, our results that are derived from a much more comprehensive array of observations.

Using the GMS-5 satellite and WSR-88D radar data, Chen (2002) studied the evolution of the rainstorm during the night of 5 August 2001. He pointed out that the continuous development of a meso-scale convective system in Shanghai was the cause of this heavy rainfall event. Using the simulations of CMA’s T106 global model and MM5 with a 27-km grid spacing, Cao (2002) analyzed the synoptic situations leading to the 5 August 2001 heavy rainfall event, including thermal and water vapor distributions. He suggested that large positive vorticity at middle and lower-level was an important factor for this event. While important, positive vorticity alone, without continuous vapor supplies, is not sufficient to produce such sustained heavy rainfall. Our analysis here points out that there was strong LLSJ passed just over Shanghai below 700 hPa, located in the southeast quadrant of a surface meso-scale low. The advection of warm and humid air by this LLSJ, leading to stronger convergence of moisture flux near Shanghai, played an important role in this heavy rainfall event.

The relationship between LLSJs, and heavy rainfall events, has been studied in other regions in the literature. For example, Chen and Yu (1988) investigated 35 rainfall events over
northern Taiwan in May–June from 1965 to 1984. They found that as in Japan and China, extremely heavy rainfall was associated with a lower-level jet. There was 84% likelihood that a lower-level jet of at least 12.5 ms⁻¹ was present at 700 hPa 12-h before the rainfall event. Analysis of this Shanghai heavy rainfall event provides further observational evidence for the role of the lower-level jet in the formation of heavy rainfall.

5. Summary

The characteristics of an extremely heavy rainfall event, observed in Shanghai on 5 August 2001 were investigated by using all available observations. The main findings of the present study are summarized as follows. Before the heavy rainfall, the synoptic situation was characterized by a north-south orientation trough at 500 hPa, a surface meso-scale low, and a surface cyclonical circulation west of Shanghai at 00 UTC 5 August 2001. A LLSJ developed on the western flank of this meso-scale low, advecting humid air to fuel the heavy rainfall.

The detailed evolution of cloud systems associated with this event was examined by using GMS-5 satellite images. These cloud systems appeared very bright in satellite images, indicative of their convective nature. The sounding observations corroborate these convective clouds: before and during the rainfall event, the atmosphere was highly unstable with CAPE values over 1633 J kg⁻¹. WSR-88D radar reflectivity of these convective systems exceeded 50 dBZ, with VIL values of 23–32 kg m⁻², suggested that rainfall was very intense. These characteristics of this Shanghai heavy rainfall event provide the benchmarks for numerical simulations, as well as useful information for forecasting such events in the future.

Acknowledgments

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Appendix

Table A1. Important Specifications of WSR-88D radar

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>S-band (10.0–11.1 cm)</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.8–3.0 GHz</td>
</tr>
<tr>
<td>Peak power</td>
<td>750 KW</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>8.5 m</td>
</tr>
<tr>
<td>Beam-width</td>
<td>0.95°</td>
</tr>
<tr>
<td>Rotation rate</td>
<td>36° per second</td>
</tr>
<tr>
<td>Pulse length</td>
<td>1.57 and 4.7 microseconds</td>
</tr>
</tbody>
</table>

References


Pradier, S., M. Chong, and F. Roux, 2002: Radar observations and numerical modeling of a pre-