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ORIGINAL PAPER

Causes of extreme rainfall in May 2013 over Henan Province: the role of the southwest vortex and low-level jet

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Abstract The present work investigated the large-scale background and possible causes of the rainstorm in Henan Province on 25–26 May 2013 using observational and numerical studies. The results indicated that this rainstorm was accompanied by widespread rainfall in China, especially Central China. The storm was caused by the eastward movement of the southwest vortex (SWV) and a strong low-level southwesterly jet, which brought adequate moisture from the Bay of Bengal and triggered a strong ascending motion. The main features of the daily rain belt and large-scale atmospheric circulation were well captured by the numerical simulation. Both observational and numerical results confirmed the essential role of the low-level southwesterly jet and its warm advection in the development and propagation of the SWV. Low-level warm advection guiding SWV propagation may provide a reference for forecasting rainfall induced by the SWV.

1 Introduction

Rainstorms, as one of the typical meteorological disasters in China, are usually accompanied by sudden and persistent gale and heavy rainfall and often cause great damage to the economy and human life (Tao 1980; Bao 2007; Ding 2014). This is in particular the case for Henan Province, which is the major grain basin for a large population. From 25 to 26 May 2013, within a valuable period for summer crops, a widespread and persistent rainstorm event occurred over Henan Province. According to statistics, daily rainfall exceeded 50/100 mm at 90/32 stations (Figs. 1 and 2), which broke historical records. Many summer crops and houses in central-eastern Henan Province were damaged, leading to huge economic losses of up to 160 million.

Previous work has noted that rainstorms in Eastern China are triggered both by large-scale atmospheric circulation and mesoscale systems (Tao 1980; Ding 1994; Gao et al. 2003; Johnson and Mapes 2003; Li et al. 2014). Among them, the southwest vortex (SWV) is known as an important heavy rainfall-producing mesoscale system (Wang et al. 2012; Fu et al. 2013). It is formed in the Sichuan Basin and has a great influence on rainfall variability over the middle–lower reaches of the Yangtze River Valley and even northern and southern China when it moves out of its origin location (Chen et al. 2007; Wang et al. 2007; Chen et al. 2015). Heavy rainfall in Henan Province is often associated with the eastward movement of the SWV (Wang et al. 2009; Wang et al. 2015), which was also the case for the rainstorm during 25–26 May 2013. Cheng (2014) and Yu et al. (2014) noted that the eastward movement of the SWV along the sheer line and adequate moisture supply caused this successive rainstorm. However, the process and dominant factors related to movement and development of the SWV in this extreme rainfall event are still not well understood. Moreover, we find that this heavy rainfall had a large-scale background along with widespread rainfall belt features from Central China to the lower reaches of the Yellow-Huai River Valley during the rainfall process. Therefore, based on previous studies, we conduct further observational and numerical investigations of this rainstorm on a national scale and diagnose the SWV activity and associated

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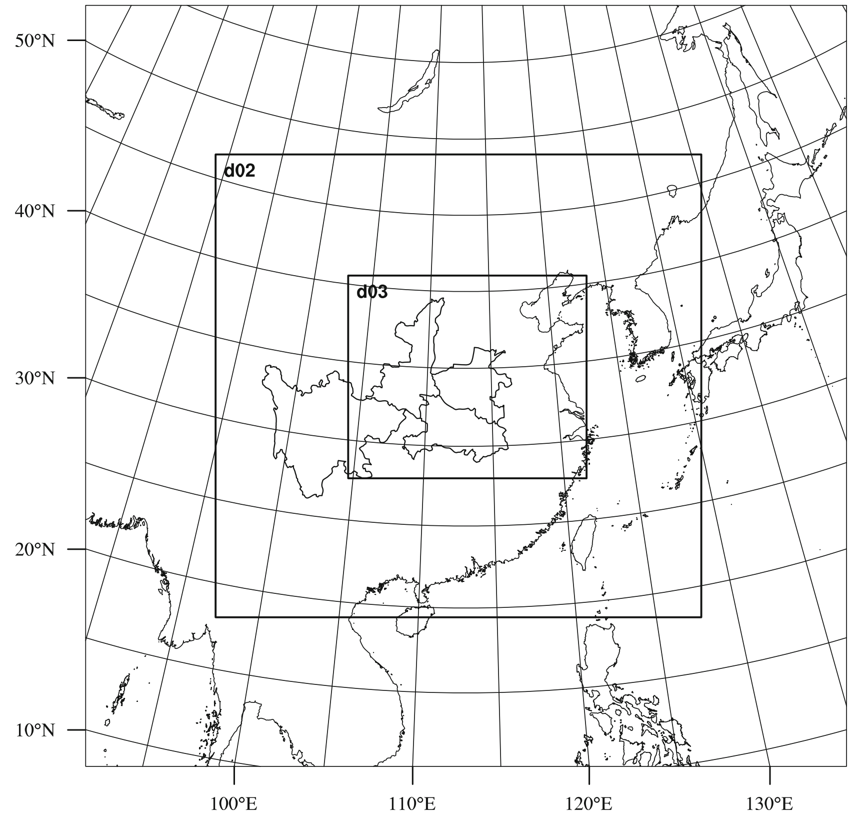


Fig. 1 The three domains in the WRF simulation. The four provinces marked in the plot from *left* to *right* are Sichuan, Shanxi, Hubei, and Henan

physical mechanism. These results may deepen the understanding of such rainstorms and provide a scientific basis for operational forecasting.

The remainder of this study is arranged as follows. Section 2 describes the data and model experiment design. Section 3 gives an overview of the rainstorm event and related large-scale atmospheric circulation. Section 4 investigates the SWV activity and associated physical processes. Finally, a summary is provided in Sect. 5.

2 Data and method

The daily rainfall (08–08 h mean) datasets were provided by two agencies. The 121 station rainfall dataset from the Henan Meteorological Bureau and the 636 station rainfall dataset from the Chinese Meteorology Administration were employed to examine local-scale and national-scale rainfall features. NCEP/NCAR daily and four-time daily reanalysis datasets were applied to explore large-scale atmospheric circulation (Kalnay et al. 1996), SWV propagation, and associated mechanisms.

In this work, we used Weather Research and Forecasting (WRF) model version 3.6 with the Advanced Research WRF (ARW) model to present the simulation study of the rainstorm. It is a non-hydrostatic mesoscale weather model with flexible resolution and multiple parameterization schemes. For this analysis, the experiment adopted 51 sigma levels with the top level to 50 hPa and chose two-way interacting nested domains with a spatial resolution of 27, 9, and 3 km, respectively. We chose the NCEP Final (FNL) six-hourly forecasting datasets with a resolution of 0.5° as the initial and boundary conditions. The simulation spanned 25 to 27 May 2013 and employed parameterization options similar to Wang et al. (2012) including the Kain-Fristsch convective parameterization scheme (Kain and Fritsch 1993), rapid radiation transfer model longwave radiation scheme (Mlawer et al. 1997), Dubhia shortwave radiation scheme (Dudhia 1989), single-moment six-class microphysics scheme (Hong and Lim 2006), Yonsei University boundary layer scheme (Hong et al. 2006), and four-layer unified Noah land surface model (Ek et al. 2003). Further details are available on the website: http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3.6/contents.html.

3 Overview of the rainstorm

3.1 Rainfall event features

Figure 2a–c shows the rainfall features in Henan Province from 25 to 27 May 2013. It is notable that during 2508–2608 May, almost all regions in Henan Province were covered

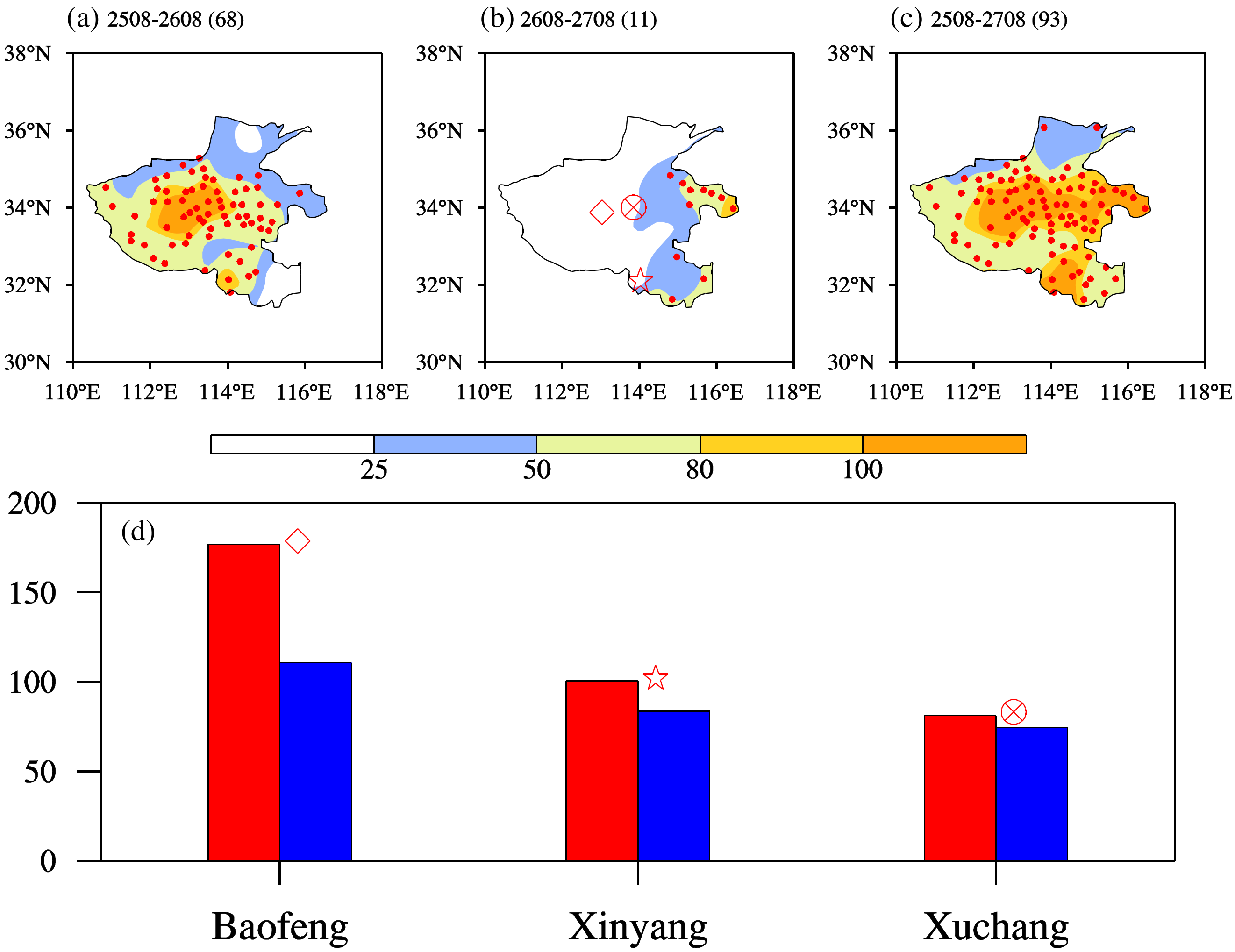


Fig. 2 The rainfall amount in Henan Province for **a** 2508–2608, **b** 2608–2708, and **c** 2508–2708. **d** The rainfall amount during 2508–2608 May 2013 in Baofeng, Xinyang, and Xuchang (*red bar*) and simultaneous historical extrema, defined as the rainfall maximum for 21–31 May from 1961 to 2012 (*blue bar*), are shown. *Red dots* denote rainfall amounts beyond 50 mm/day, and the locations of the three typical stations are plotted in Fig. 2b marked as a *diamond*, *star*, and *arrow tail*

by heavy rainfall, having daily rainfall amounts exceeding 50 mm at 68 stations and a maximum center in central-western Henan Province. The rainfall belt moved eastward to eastern Henan on 26–27 May, with daily rainfall amount surpassing 50 mm at 93 stations, especially over central-eastern Henan. The rainfall amount at many stations broke historical maximum records, such as at Baofeng, Xinyang, and Xuchang (Fig. 2d).

As shown in Fig. 3a–c, this rainfall event had a large-scale background with a widespread rainfall belt spreading from Central China to the lower reaches of the Yellow-Huai River Valley. On 24 May, the major rainfall center was situated over eastern Sichuan Basin; on 25 May, it moved to Central China, with heavy rainfall in Henan and Hubei provinces. On 26 May, the main rainfall belt moved to Shandong Province and then out of mainland China. The model simulation successfully captured both rainfall belt movement and the rainstorm in Henan and Hubei provinces on 25–27 May. The modeled rainfall intensity is greater than that observed, especially over southern China (Fig. 3d, e), which may be attributed to a discrepancy in initial condition forcing in the FNL dataset compared to observations.

For subdaily rainfall features, both rain belt distribution and its eastward movement in the observation and simulation exhibited similar characteristics to the daily mean features, and the simulated rainfall intensity was also greater than that of the observation (figure not shown). Here, the 3-h rainfall evolutions of the rainfall belt zonal averaged over 30–35° N are presented to show subdaily features in observation and simulation. As shown in Fig. 4a, a notable rainfall process was observed over central-eastern China from 25 to 26 May, and strong rainfall occurred during the period 2514–2605, with two extreme centers east of 112° E. The simulated rain belt distribution and its eastward movement resembled those in the

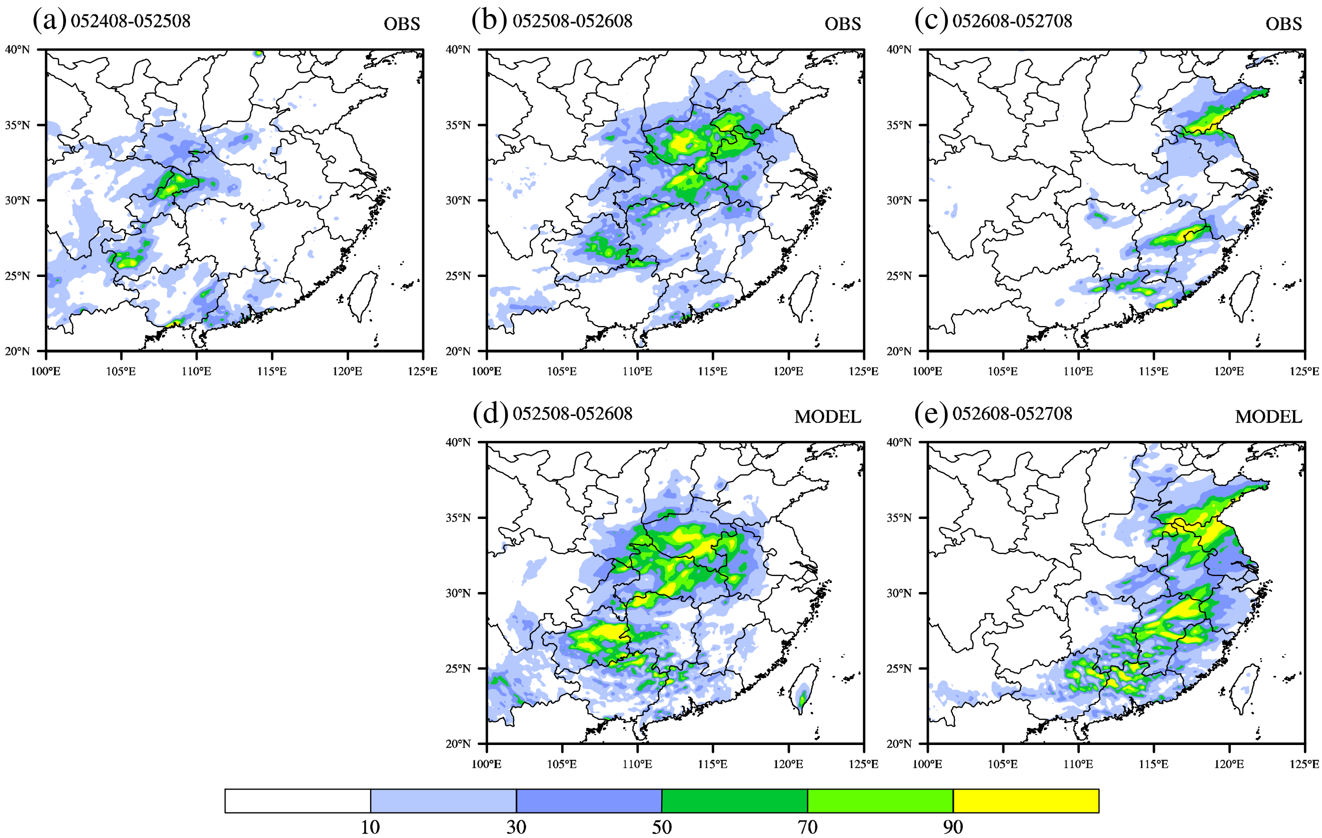


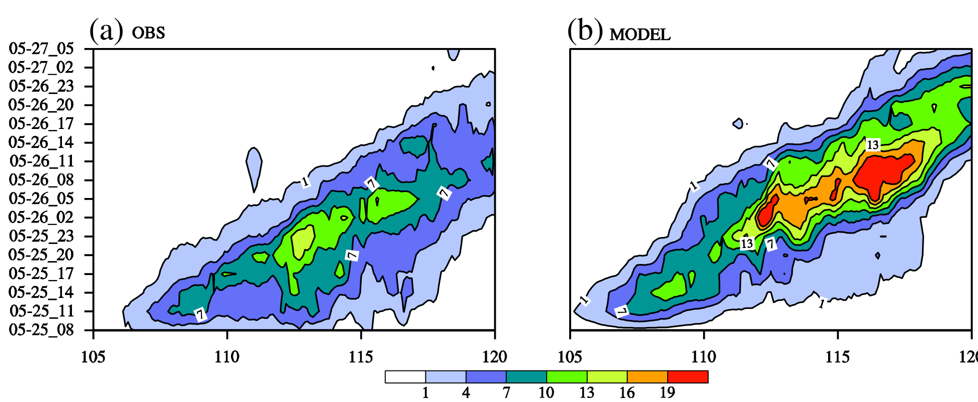
Fig. 3 Observed (*top*) and simulated (*bottom*) daily rainfall amount in China from 24 to 26 May 2013 (unit: mm/day)

observation, but the amplitude of the simulated rainfall was much larger, the rainfall period lasted much longer, and the simulated extreme rainfall appeared later than the observation. These discrepancies may arise from two aspects. One is the larger rain belt and rainfall amplitude in the simulation, which was associated with the model's ability to accurately reproduce the rainfall belt and rainfall amplitude, especially on subdaily timescale. The other is the uneven distribution of the few observation stations in China, which may not provide comprehensive information of the rainfall event, such as stronger rainfall in some places were not observed.

3.2 Large-scale atmospheric circulation

Large-scale atmospheric circulation and abundant moisture supply play essential roles in triggering heavy rainfall in China (Tao 1980; Tao and Ding 1981; Ding 2014). The heavy rainfall event was accompanied by a deep trough/vortex passing over mainland China (Fig. 5a–c). On 24 May, a deep southwest-northeast tilting trough emerged over southwest China and supplied strong moisture along its front, which caused strong moisture convergences and ascending motion and led to heavy rainfall over Sichuan Basin and southern

Fig. 4 Longitude-time evolution of zonal-averaged rainfall over 30–35° N: **a** observation and **b** model



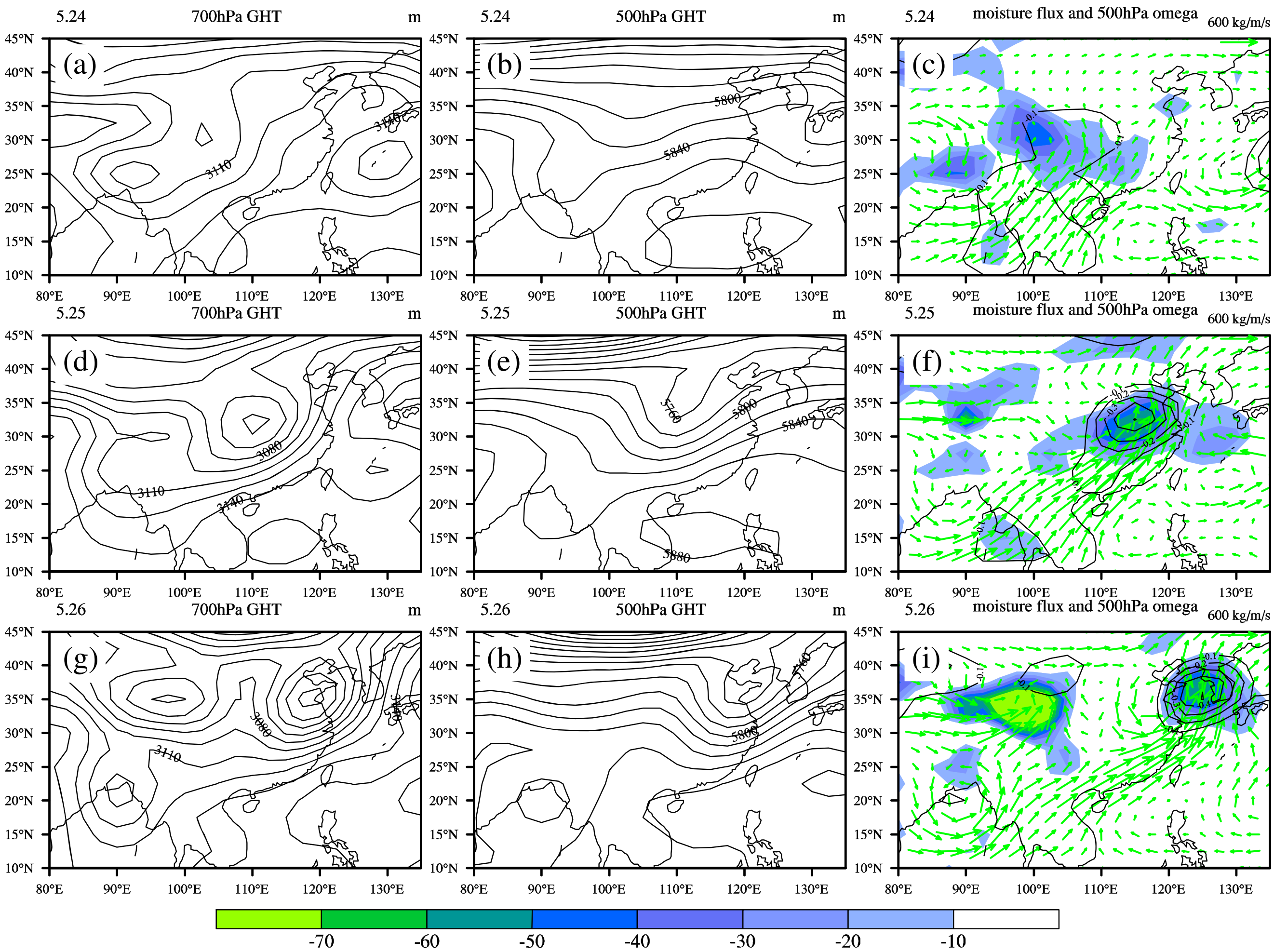


Fig. 5 The daily geopotential height (unit: m) at 700 (**a**, **d**, **g**) and 500 hPa (**b**, **e**, **h**). Vertical integrated water vapor flux (vector with unit kg/m/s) and its divergence (shaded with unit mm/day) and vertical velocity at 500 hPa (contour with unit Pascal/s) from 24 to 26 May 2013 (**c**, **f**, **i**)

Shanxi Province. On 25 May, the deep trough enhanced and moved eastward to Central China; the moisture transportation/convergence and ascending motion strengthened and shifted eastward, which resulted in rainstorms over Henan and Hubei provinces (Fig. 5d–f). The synoptic systems and rain belts moved eastward further to Eastern China on 26 May (Fig. 5g, h). Therefore, the movement and enhancement of the trough/vortex from Sichuan Basin, the strong moisture transportation from the Bay of Bengal, and the strong ascending motion in the front of the trough/vortex (Fig. 6b, d) were key factors related to the rainstorm over Central China.

The main features of the large-scale atmospheric circulation were also well captured by the model simulation. Here, we explored the simulated 700 hPa vorticity and 500 hPa vertical velocity, which to some extent represent vortex movement and the rainfall belt. As shown in Fig. 6a, c, both the location and intensity of the simulated 700 hPa vorticity from 25 to 26 May matched the observation very well. The model captured the location of notable ascent, but the intensity of the simulated vertical velocity is half that of the observation.

4 Activity of the SWV, temperature advection, and jet stream

As discussed in Sect. 3, the severe rainfall in Central China from 24 to 26 May was attributed to the eastward propagation of the SWV from Sichuan Basin (Figs. 7 and 8). In this section, we explore the development and propagation of the SWV and its association with warm advection and jet stream, which are of great importance to operational forecasts. This analysis indicated that the strong moisture transportation (Fig. 5c–i), ascending motion (Fig. 6), and high-level/low-level jet stream (Figs. 7 and 8) accompanied by the SWV played essential roles in the rainstorms in Henan and Hubei provinces.

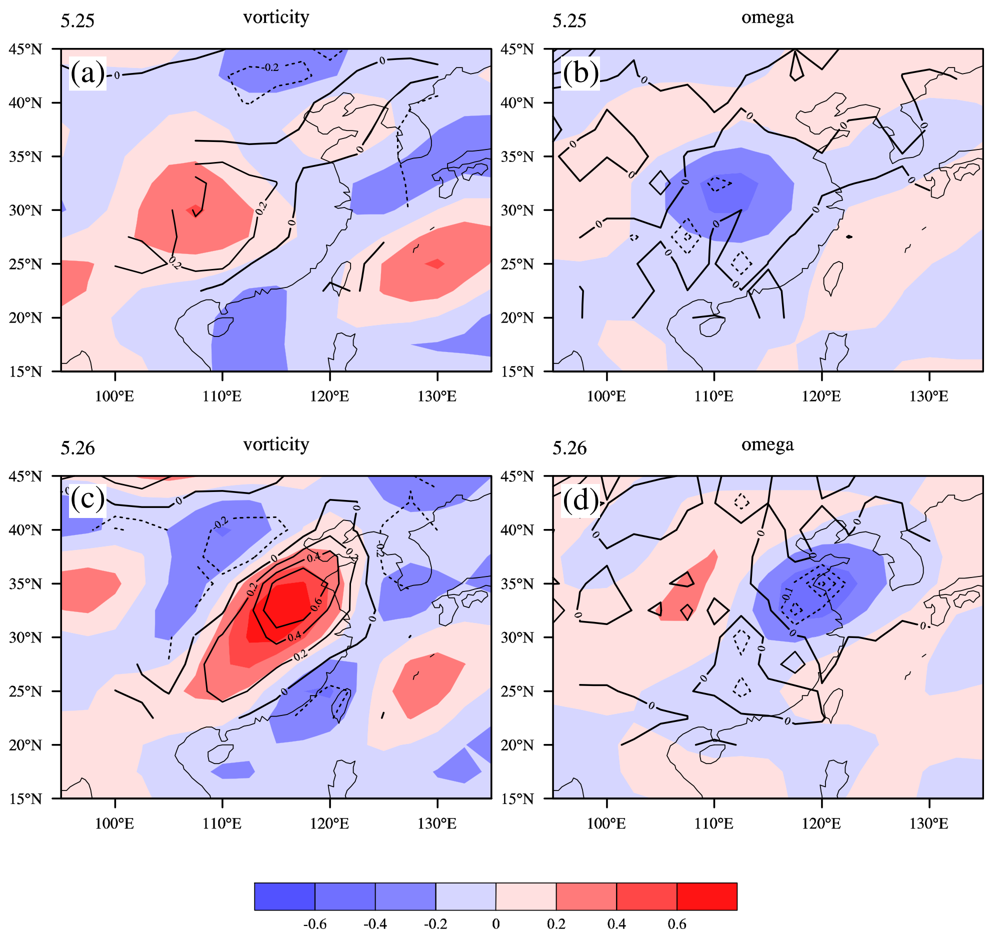


Fig. 6 Observed (*shaded*) and simulated (*contour*) 700 hPa vorticity (**a**, **c**, unit: s^{-1}) and 500 hPa vertical motion (**b**, **d**, unit: Pascal/s) from 25 to 26 May, 2013. The vorticity is amplified by 10^4

4.1 Activity of the SWV

First, we analyzed the daily mean streamlines at 700 hPa, which is usually adopted to study the SWV. As shown in Fig. 7a–c, the SWV was generated in the eastern Tibetan Plateau and Sichuan Basin on 24 May and propagated eastward out of the Sichuan Basin with enhanced intensity. From 25 to 26 May, the SWV center moved to the eastern Sichuan Basin/Henan Province, and its intensity strengthened. The simulated daily mean SWV resembled that of the observation, except its intensity was weaker and its location shifted eastward. These features were clearer in the subdaily evolutions of the SWV, which are displayed in Fig. 8. Here, we used the relative vorticity at 700 hPa to study SWV. At approximately UTC 2013052412, the SWV formed in the Sichuan Basin and propagated northeastward with intensifying strength. During the period UTC 20130522500 to 2013052606, the SWV moved slowly over central and eastern China, resulting in rainstorms in Henan and Hubei provinces.

From Figs. 3 and 7, we observe that the strong rainfall belts were situated approximately 5° east and south of the SWV centers, where suitable atmospheric configurations, such as adequate moisture supply and strong ascending motion, were favorable for heavy rainfall.

4.2 The role of the jet stream and the temperature advection

Previous studies have revealed that low-level and high-level jet streams are also important synoptic systems for triggering heavy rainfall in China (Tao 1980). We found that the extreme low-level southwesterly jet played an essential role in this rainstorm. As shown in Fig. 7, the strong southwesterly jet prevailed over southern China and moved eastward from 25 to 26 May. It intensified with time, and its strength exceeded the historical relative extremes (red area in Fig. 7) over southern China. Here, the relative extreme was defined as the 90th percentile of all wind speeds for 21–31 May from 1948 to 2014 (Zhai et al. 2005). The extreme low-level southwesterly jet brought abundant water vapor to the Central China and provided beneficial water vapor conditions. Additionally, it transported prominent warm air to southern and central China, and the remarkable warm advection reduced air pressure, which favored the genesis/enhancement of the SWV and triggered strong ascending motion. Typical dynamic and

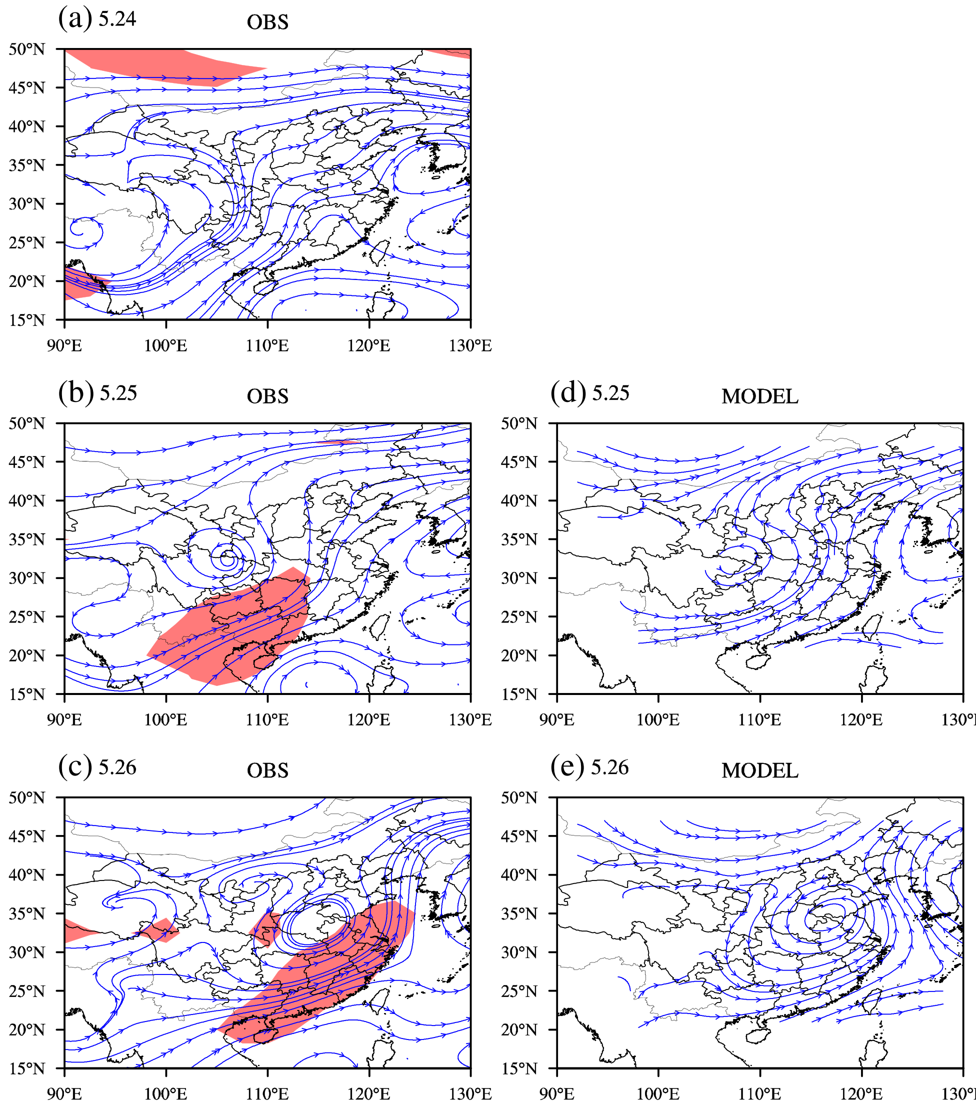


Fig. 7 Observed (**a**–**c**) and simulated (**d**–**e**) 700 hPa streamlines. The *shaded areas* denote regions where wind speed exceeded historical relative extremes (unit: m/s)

thermodynamic configurations led to the rainstorms in Central China.

Furthermore, we analyzed the subdaily features of the low-level southwesterly jet and its warm advection, as well as the relationship to the SWV in this rainfall event; the results are shown in Fig. 8. At approximately UTC 2013052412, the SWV formed in Sichuan Basin moved eastward and intensified with time. Remarkably, the evolution of SWV (relative vorticity) was closely related to warm advection induced by the low-level southwesterly jet, in particular meridional temperature advection (figure not shown). The maximum centers of warm advection preceded those of the relative vortices (cyclonic winds) approximately 5°, suggesting a role of warm advection in guiding movement of the vortex/SWV. Intensification of the SWV may be due to enhancement of the low-level jet and its warm advection, and, in turn, the enhanced SWV favored strengthening and persistence of the low-level jet. The interaction between the SWV and low-level southwesterly jet plus the beneficial water vapor condition led to heavy rainfall in Central China. In addition, the latent heat release from heavy rainfall further reduced the low-level pressure and increased the meridional pressure gradient, resulting in acceleration and persistence of the southwesterly jet.

The model simulation captured the main features of the SWV activity (Fig. 7d, e) and low-level jet, as well as the temperature advection (figure not shown), suggesting significant roles of the SWV and low-level southwesterly jet in triggering heavy rainfall in Central China.

In addition, mid-latitude trough/ridge activity contributed to the development and movement of the SWV by cold advection and vorticity advection (Figs. 5 and 7). The stable high subtropical over the western Pacific from 24 to 26 May (Figs. 5–7) on one hand brought warm wet air to inland China and on the other hand favored the eastward propagation

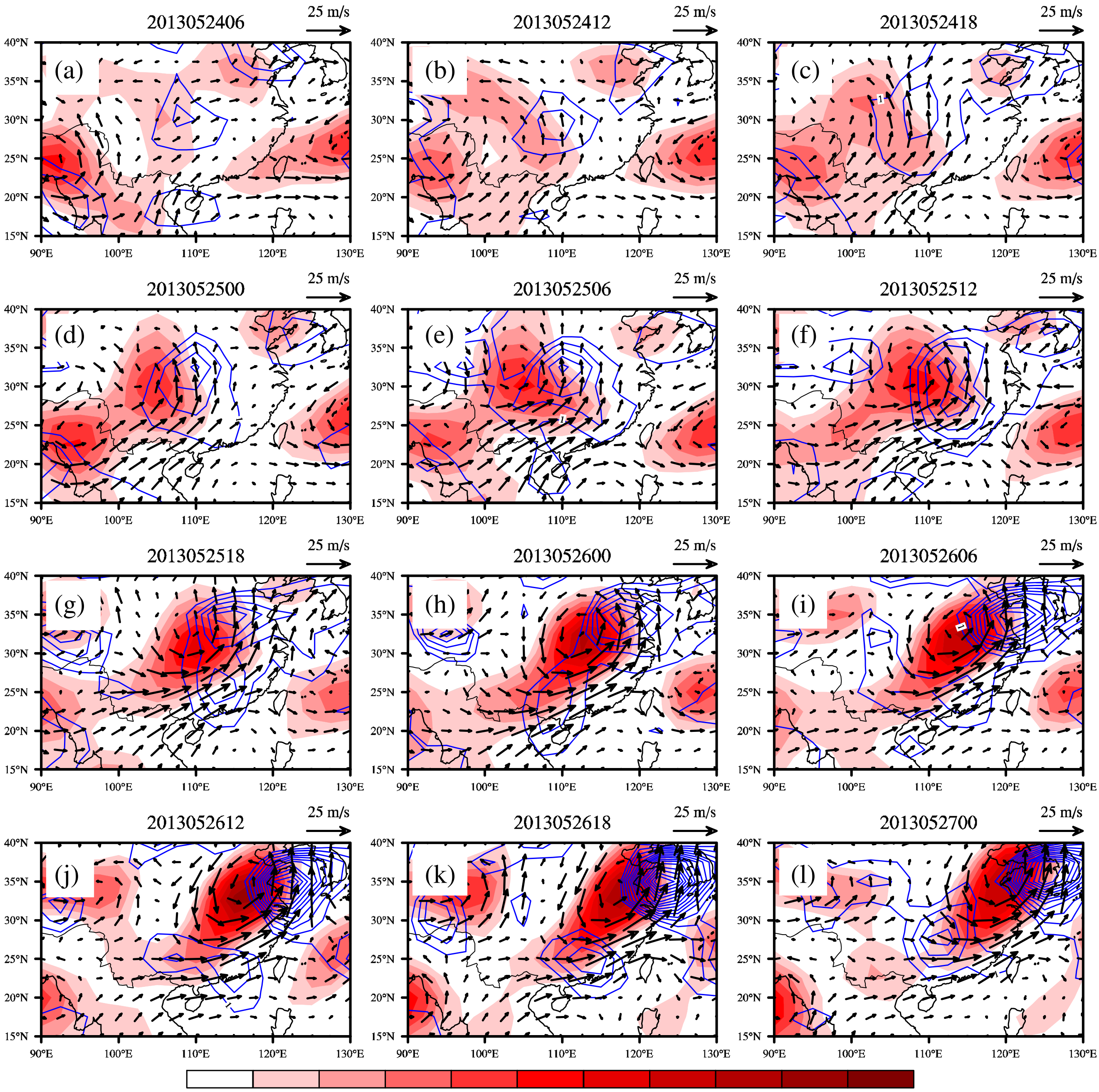


Fig. 8 Relative vorticity (*shaded*, unit: s^{-1}), warm advection (*blue contour*, unit: K/s), and horizontal winds (*vector*, unit: m/s) at 700 hPa from UTC 2013052406 to 2013052700

of the SWV and the persistence of the southwesterly jet. The favorable configurations of atmospheric circulation caused the rainstorms in Central China.

5 Conclusion and discussion

During 25–26 May 2013, a severe rainfall struck Henan Province and led to extensive damage. Using observational and reanalysis datasets and numerical simulation, the large-scale background and possible causes related to rainstorms were studied in the present work.

The results indicated that widespread rainfall in China accompanied the rainstorms from 24 to 26 May, especially in Central China. The rainfall was caused by eastward movement of the SWV and an extreme low-level southwesterly jet, which brought adequate moisture from the Bay of Bengal and triggered strong ascending motion through warm advection. The main features in the rain belt and large-scale atmospheric circulation were captured well by the numerical simulation despite its reproduction of an inaccurate rain belt and amplitude on the subdaily timescale. Both observational and numerical studies revealed that the low-level jet/warm advection played essential roles in the development and propagation of the SWV, and warm advection may have a guiding role in the movement of the SWV. Maintenance of the subtropical western Pacific high and mid-latitude trough/ridge activity also contributed to the development and propagation of the SWV and further resulted in heavy rainfall from 24 to 26 May. That low-level warm advection guides the SWV propagation may provide a potential reference for forecasting rainfall induced by the SWV.

An additional numerical simulation beginning on 24 May was also conducted. The results revealed that the features and configuration of the rain belt, SWV, and low-level jet were further from observation than the experiment beginning on 25 May, especially over the Tibetan Plateau and the Sichuan Basin, where the SWV was generated. On the basis of sensitivity experiments, Wang and Gao (2003) noted that the eastward-moving SWV was sensitive to the initial forcing condition, which directly impacts the rain belt distribution. Thus, these discrepancies in the initial condition and atmospheric background related to the SWV generation are important issues influencing model results in accurately reproducing rain belt and amplitude.

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