Role of Boundary Layer Jet in the Occurrence and Development of Warm-sector Heavy Rainfall over South China: a Case Study

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Abstract. Warm-sector heavy rainfall which occurred at the coastal area of southern China on 8 June 2015 was associated with a boundary layer jet (BLJ). The initiation and maintenance mechanism of the BLJ is further investigated based on the Weather Research and Forecasting (WRF) model simulations and reanalysis data. The results showed that the BLJ developing at night transported moisture to the coastal area of Guangxi in southern China, which lead to the instability of the atmosphere over the coastal areas of Guangxi. The terrain blocking and lifting the southerly with abundance of water vapor is the major trigger mechanism in present case. As the BLJ weakened and vanished after midday, the amount of rainfall decreased correspondingly. Based on the numerical model sensitivity test with different parameterization schemes, the key role of the BLJ for the occurrence and development of the warm-sector heavy rainfall is further verified.

Keywords: Boundary layer jet; Warm-sector heavy rainfall; South China; WRF.

1. Introduction
Southern China is a region with the largest number of rainfall events and the largest average annual rainfall in Mainland China [1-3]. During the pre-summer rainy season, extremely heavy rainfall over southern China often occurs in the warm sector, an area of a few hundred kilometers ahead to the south boundary of a cold front, or the area dominated by warm air without front in the south of the Nanling Mountains [4]. This kind of heavy rainfall is called warm-sector heavy rainfall (WSHR). Many studies have shown that there are significant differences between the WSHR and frontal rainfall in the trigger and maintenance mechanisms as well as the dynamic and thermodynamic structures [5-6]. Low-level jets (LLJs) occur frequently over southern China [7-8]. Since the LLJs are closely related to rainfall, they have been widely studied by meteorologists [9]. The LLJs can be further classified into two types, namely, the boundary layer jet (BLJ), which occurs below the 900hPa in South China Sea (SCS), and the synoptic-weather-related low level jet (SLLJ), which occurs in the layers higher than the BLJ [10]. Recently, more studies of WSHR and LLJ in southern China have been conducted. Based on a case study, Du and Chen found that the SLLJ and BLJ are closely related to the rainbands in the inland frontal zone and in the coastal warm sector, respectively [7-8].
and Meng [11] found that 64% of WSHR episodes are associated with LLJ, and DLLJ type (both BLJ and SLLJ occur). Nevertheless, the interactions between the LLJ especially the BLJ and WSHR are not yet clear, and still need to be investigated.

2. Numerical Model and Data

2.1. Model

The Weather Research and Forecasting (WRF) model version V3.6.1 is used to investigate the trigger mechanism and the role of the terrain and the BLJ in present case. The model configuration consists of nested grids with horizontal grid spacing of 12 km (240×240 grid points) and 4 km (421×451 grid points) and 42 levels from the earth surface to the 50hPa level (Figure 1a). Key model physics options for the control run (CTRL) include Lin scheme for microphysics, Yonsei University scheme for planetary boundary layer, Monin-Obukhov scheme for surface layer, Noah scheme for land surface, and Dudhia scheme and Rapid Radiative Transfer Model scheme for shortwave and longwave radiation, respectively. For cumulus parameterization scheme, Kain-Fritsch scheme is used in 12 km grid spacing domain, but turned off in the 4 km grid spacing domain. A sensitive experiment similar to the CTRL, but the microphysics scheme is replaced by New Thompson scheme (mp_NT), is performed to examine the key role of the BLJ in current case. The WRF model is initialized at 1800 UTC on 7 June 2015 for a 18 hours simulation by using the FNL reanalysis data of National Centers for Environmental Prediction of the United States as the initial and boundary forcing data.

![Figure 1](image)

**Figure 1.** (a) WRF nested domains simulation; (b) The 24–h accumulated rainfall amount during the period of 2000 LST 7 June to 2000 LST 8 June 2015 (units: mm), the black box denotes the major rainfall area; (c) The averaged hourly precipitation over the black box in Figure 1b (units: mm).

2.2. Data

The hourly precipitation data used in this study is merged by gauge data at more than 30000 automatic weather stations in China and Climate Precipitation Center Morphing (CMORPH) precipitation product with a high spatial (0.1×0.1) and temporal (1h) resolution (AWS-CMORPH). Previous studies have shown the reliability of AWS-CMORPH in the Mainland China [12]. In addition, the Interim European Centre for Medium-Range Weather Forecasts reanalysis data (ERA-interim) with a 0.25° spatial resolution and 6h time intervals are utilized to analyze the synoptic circulation.

3. Results

3.1. Overview of Rainfall and Synoptic Circulation

An extreme rainfall event took place on the coastal area of Guangxi during the period of 0000 LST (local standard time) to 1800 LST on 8 June 2015, with the maximum 24h accumulated rainfall amount of 188.44mm (Figure 1b). The large-scale atmospheric circulation of present rainfall case was neither affected by shear line nor low vortex system and was located hundreds of kilometers away from frontal rainband (Figure 1b), which showed the typical characteristics of warm sector heavy rainfall [4]. Time series of the hourly rainfall averaged in the black box as shown in Figure 1b
exhibited a one-peak pattern, with the major rainfall occurring at 1000 LST-1500 LST (Figure 1c).

Figure 2. The ERA-interim analysis at 2000 LST on 7 June (a-c), 0200 LST (d-f) and 0800 LST (g-i) on 8 June 2015. (a,d,g) The 850hPa geopotential height (blue line, units: dgpm), 850hPa $\theta_e$ (shaded, units: K) and 925hPa horizontal wind barbs (a full barb is 8 m s$^{-1}$, with the wind speed larger than 12 m s$^{-1}$ plotted in bold wind barbs), the brown dash line and black solid line denote the shear line and the the S-N cross sections used in Figure 2 (b,c,e,f,h,i), respectively. (b,d,f) Composite cross section of meridional wind (vector, units: m s$^{-1}$), vertical wind (vector, units: 10 cm s$^{-1}$) and water vapor flux (shaded, units: g·cm$^{-1}$·hPa$^{-1}$·s$^{-1}$). (c,f,i) Composite cross section of the divergence of water vapor flux (units: 10$^{-6}$g·cm$^{-1}$·hPa$^{-1}$·s$^{-1}$).

The rainfall area was located in the southeast of the South Asian high and the right-hand side of the upper westerly jet at 200hPa, which was beneficial for the occurrence and maintenance of rainfall due to the divergence in the upper layer (not shown). At 500hPa, the western Pacific subtropical high (WPSH) was extended to the west of 110°E. A shear line was present over the north of southern China in the lower troposphere, which roughly corresponded to the pseudo-equivalent temperature ($\theta_e$) of 345 K at 850hPa (Figure 2). Du et al. (2019) used the following criteria to identify the existence of a BLJ: 1) the maximum wind speed is more than 10 m s$^{-1}$ below 1km; and 2) below 600 hPa the wind speed must decrease by at least 3 m s$^{-1}$ from the height of the wind maximum in the boundary layer to the wind minimum above that. According the criteria above, the BLJ existed in southern China, with the BLJ core located at Gulf of Tokin. As shown in Figure 2, BLJ below the 900hPa developed at night due to the inertial oscillation, and further affected the thermodynamic conditions by transporting water vapor to the rainfall area. The double LLJs and local topography provided the strong convergence under the 900hPa in the coastal area of Guangxi, where the WSHR occur. Nevertheless,
the WSHR is not sensitive to the SLLJ [7]. The main reasons are as follows: 1) The SLLJ is mainly located in the north of WSHR area, thus SLLJ is unable to transport plenty of water vapor from the SCS to the WSHR area (Figure 2); and 2) The level of SLLJ is higher than the average height of local terrain (below the 925hPa), which means that the SLLJ is likely to pass over the mountain instead of being blocked by the mountain.

In summary, the LLJ, especially the BLJ is essential for the initiation and maintenance of the WSHR in southern China. Nevertheless, the investigation of the synoptic scale system is not enough for present study, the mesoscale system characteristics simulated by WRF model will be further discussed in the next section.

3.2. Mesoscale Characteristics Analysis

We checked the model performance in Figure 3. It shows that the coastal warm-sector rainband can be well captured by the WRF simulation though simulated time of the convection initiation was delayed about 2-3 hours, partly due to the spin-up of the simulation, and the simulation overestimates the precipitation amount slightly. The model can also capture the major features for the linear-shaped mesoscale convective systems (MCSs) compared to the observation (not shown).

The vertical cross section of θse, CPAE, and CIN are analyzed as shown in Figure 4. Both θse (Figure 4a) and CAPE (Figure 4b) were large at near-surface layers below 900hPa owing to the transportation of warm and moisture air by BLJ (Figure 5a), which developed at night due to the inertial oscillation proposed by Blackadar, and decreased rapidly in the higher level. The low CIN (Figure 4c) zone around 0 J kg\(^{-1}\) occurred below the 900hPa, especially near the windward slope of local terrain. Therefore, such thermal condition is favorable for the initiation of the MCSs.

Because of the effect of the coastal terrain on the BLJ, strong convergence and vertical motion occur near the terrain (Figure 5). The maximum vorticity and vertical velocity can reach \(3\times10^4\) s\(^{-1}\) and 3m s\(^{-1}\), respectively. In summary, BLJ and coastal terrain provide the thermal and dynamical conditions for the initiation and maintenance of the WSHR, respectively. Thus, the clouds at low levels were first formed near the coastal terrain at 0400 LST in the WRF simulation and increased with time as shown in Figure 5. The BLJ disappeared in the afternoon gradually (not shown), causing the precipitation to dissipate a few hours later.

Therefore, the major effects of BLJ on rainfall over South China in this case are as follows: 1) transport water vapor from South China sea (Figure 2); and 2) dynamic forcing lifting with windward slope (Figure 5).
Figure 3. 3h accumulated precipitation (units: mm) of observations (a-f) and WRF simulation (g-l).

Figure 4. Composite vertical cross sections at the 0400 LST (a-c), 0600 LST (d-f) and 0800 LST (g-i) on 8 June 2015 revealed by WRF simulations along the black line in Figure 2a, including (a,d,g) relative humidity (units: %) and potential pseudo-equivalent temperature (units: K), (b,e,h) CAPE (units: J kg$^{-1}$) and (c,f,i) CIN (units: J kg$^{-1}$).
Figure 5. Composite vertical cross sections at the 0400 LST (a-d), 0600 LST (e-h) and 0800 LST (i-l) on 8 June 2015 revealed by WRF simulations along the black line in Figure 2a, including (a,e,i) wind speed (shaded, units: m s\(^{-1}\)), meridional wind (vector, units: m s\(^{-1}\)) and vertical wind (vector, units: 10 cm s\(^{-1}\)), (b,f,j) voricity (units: 10\(^{-5}\) s\(^{-1}\)), (c,g,k) vertical velocity (units: cm s\(^{-1}\)) and (d,h,i) temperature (contour, units: °C) and cloud water mixing ratio (shading, k kg\(^{-1}\)).

3.3. Sensitivity Test
In order to explore the role of the BLJ in the WSHR, a sensitivity experiment (mp_NT) during the same period was conducted, in which the microphysics scheme was replaced by New Thompson scheme as shown in Figure 6a,e. Figure 6 shows the difference in 24-h accumulated rainfall amount, wind speed, vorticity and vertical velocity between the CTRL experiment and the sensitivity experiment mp_NT. It is apparent that the BLJ in the CTRL is stronger than that in the mp_NT experiment. Thus, the intensity of the vorticity and vertical velocity near the coastal terrain is lower in mp_NT experiments, and eventually influences the precipitation amount of the WSHR.
Figure 6. 18–h accumulated rainfall amount of CTRL (a) and mp_NT (e) during the period of 0200 LST to 2000 LST 8 June 2015. Composite vertical cross sections of at the 1000 LST on 8 June 2015 simulated by CTRL (b-d) and mp_NT (e-h) along 108.5°N, including (b,f) wind speed (shaded, units: m s\(^{-1}\)), meridional wind (vector, units: m s\(^{-1}\)) and vertical wind (vector, units: 10 cm s\(^{-1}\)), (c,g) vorticity (units: 10\(^{-5}\) s\(^{-1}\)) and (d,h) vertical velocity (units: cm s\(^{-1}\)).

4. Summary
In this study, we examined the synoptic and meso-scale weather processes which influence the WSHR case during the period of 0000 LST to 1800 LST on 8 June 2015 over coastal area of Guangxi using the reanalysis data and WRF model simulation and sensitivity experiment. The WSHR case was found to occurred several hundred kilometers to the south shear line. As a result, two types of southeasterly low level jets occurred over southern China, including the BLJ and SLLJ. The BLJ located in the Gulf of Tonkin transported moisture to the coastal area of Guangxi during the night and early morning. The WSHR occurred as warm and moist air in the planetary boundary layer was lifted by local topography. The sensitivity experiment further proved that the BLJ is not only related to the thermal stability in coastal area of Guangxi, but the convergence produced by the interaction between the BLJ and terrain is also essential to the initiation and maintenance of the WSHR.

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