The heavy rainfall during the warm season over the Pearl River Delta region: Movements and early signals

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Abstract
The environments and movement, as well as the surface characteristics of heavy rainfall (HR), were examined based on 5-year HR episodes collected from the surface observations during the warm season (April–September) from 2015 to 2019. The results showed that the HR generally exhibited eastward movement with average moving-speed of 59 km hr−1 over South China. The daytime HR exhibited more episodes and faster moving-speed than the nocturnal HR. Both nocturnal HR and daytime HR were strongly influenced by the southerly wind during April–June over the Pearl River Delta (PRD) region. It showed a cyclonic wind pattern during the occurrence-time of nocturnal HR and a strong early convergence belt at −3 hr of daytime HR between the southeasterly winds and the northeasterly winds over the north part of the PRD region, which might be related to the cold outflow from the upstream east-moving convections. Another key characterization parameter of HR was the strong decrease of surface potential temperature over the PRD region, especially during July–September.

KEYWORDS
heavy rainfall, surface observations, the Pearl River Delta region, cyclonic wind pattern, early convergence belt

1 | INTRODUCTION

Heavy rainfall (HR) occurs most frequently during the warm season in South China (Tao, 1980). The Pearl River Delta (PRD) region, one of the world’s largest urban agglomerations in terms of population and coverage area, has been identified as one of the HR centers in South China (Tao, 1980). Observational analysis indicates that more extreme rainfall events take place with rapid urbanization over the PRD region (Yan et al., 2020). An extreme rainfall event was the record-breaking hourly rainfall rates of 184 mm hr−1 over the megacity of Guangzhou on May 7, 2017 (Yin et al., 2019). Investigations of HR over the PRD region are critical for understanding the corresponding characteristics and mechanisms of HR during the warm season.

For the early signals of the HR over South China, some recent studies attributed the HR (especially the nocturnal-to-morning rainfall) to the early enhanced low-level southwesterly flow (Chen et al., 2017; Jiang et al., 2017; Chen et al., 2018; Zhong et al., 2019a) and diurnal inertial oscillations of boundary layer south-southwesterly low-level jets (LLJs) (Zhang et al., 2019). Zhang and Meng (2019) found that 64% of the...
warm-sector HR episodes were associated with the southerly LLJs. The rainfall was mainly triggered by the divergences between the early enhanced southerly wind and northerly land breezes over the mountainous areas (Chen et al., 2016; Zhong, 2020), as well as the contributions by local topographic lifting and blocking and surface heating (Chen et al., 2015, 2016; Jiang et al., 2017; Chen et al., 2018; Zhong et al., 2019a) and the regulations by large scale circulation over the Asian monsoon regions (Chen, 2020).

Note that the cold outflow by the previous convection could generate subsequent convections (Fujita et al., 2010; Wu and Luo, 2016), it is important to investigate the evolutions of the HR, especially for the movement of upstream convections. It was pointed out that new convective cells were continuously generated along the boundary between the cold outflows of previous convection and the southeasterly flow from the South China Sea (Wu and Luo, 2016). Moreover, the cold pool dynamics play an essential role in the inland penetration of precipitation and the sea breeze (Chen et al., 2016). In the daytime, HR could be caused by the enhanced southerly wind and northerly wind over the mountainous areas (Zhong, 2020), and propagated inland with the inland penetration of the sea breeze. In the night, the mountain–plain solenoid combined with the land breeze could enhance offshore convergence.

Investigations of the movements of HR over the PRD region could help to better understand the corresponding characteristics and possible early signals associated with HR. The PRD region has the densest observation stations over South China. There are more than 1,300 stations with an average horizontal resolution at about 2 km. The high spatiotemporal data have been widely used in daily weather forecasting, model verification, and weather analysis (Tian et al., 2015; Zhu et al., 2018; Zhang and Meng, 2019; Zhong et al., 2019b; Zhong and Chen, 2020). Based on 5 years of HR episodes collected from 2015 to 2019, the present study tries to examine the specific movements and structure of HR and reveal the early signals associated with HR over the PRD region in South China. Two rainy seasons during April–June and June–September are discussed separately in view of the possible differences of physical mechanisms (for example, more warm-sector HR in April–June and strong tropical-cyclone HR in June–September) during the warm seasons (Chen et al., 2013; Chen et al., 2016; Jiang et al., 2017).

2 | DATASET AND METHODS

Detailed weather data obtained from about 13,032 automatic weather stations over South China were used in this study. The surface meteorological variables extracted from this dataset include surface temperature, pressure, specific humidity, surface wind, and rainfall amount at 1 hr intervals during April–September over the years 2015–2019. The data were subjected to quality control for various operational utilization by the South Meteorological Center of China Meteorological Administration (Zhong and Chen, 2020). The fifth-generation (ERA5, Olauson, 2018) of atmospheric reanalysis with the horizontal resolution at 25 km of the global climate from the European Centre for Medium-Range Weather Forecasts (ECMWF) was also used to perform the large-scale composite analyses.

In this study, the definition of an HR episode was given under three assumptions. Firstly, the hourly rainfall exceeded 20 mm at more than three stations was considered the threshold for an HR episode. Secondly, the distances between the stations within the radius \(\sigma\) (\(\sigma = 200\) km, to discriminate the HR from other weather systems, for example, the front system, Liu et al., 2018) are classified into the same category of HR. Finally, with the satisfaction of the previous two conditions, the average location of the same category of HR stations was defined as the HR center, and the hourly moving distance of a certain rain belt was limited to \(\sigma\). The time range of daytime HR refers to the HR occurred between 9 a.m. and 8 p.m. at the local time and the nocturnal HR refers to the HR occurred between 9 p.m. and 8 a.m. in the next day. To calculate the moving speed of each rain belt, the closest HR center at the previous hour within the radius was defined as the upstream point. The average field \(\bar{V}_i\) at each station was calculated by introducing at an impact radius (\(\gamma\)) around the HR center.

\[
\bar{V}_i = \frac{1}{N} \sum_{t=1}^{N} V_i(t), \gamma_i < 50\text{ km}
\]  

where \(N\) is the sample of days, \(i\) stands for the station number, and \(\gamma_i\) is the distance between surface observation and the HR center.

3 | RESULTS

The HR mainly located in the coastal regions over the South and Southeast of Guangdong, as well as the southern coastal regions and northern mountainous areas of Guangxi (Figure 1), including the HR centers located over the PRD region and at the windward slope of the mountainous areas. The total accumulative rainfall over the PRD region reached more than 11,000 mm and the amount of HR reached more than 3,500 mm. Most of HR
FIGURE 1  The distribution of (a) accumulative precipitation (dots, units: 1000 mm) and (b) the amount of the heavy rainfall (>20 mm·hr⁻¹); (c) the observational stations over South China, the black rectangle denotes our target domain, and (d) the distribution of HR movements, the black vectors denote the eastward-moving of HR and the red vectors represent the westward-moving of HR.

FIGURE 2  Comparisons of the movements of (a, c) daytime and (b, d) nocturnal HR (km·hr⁻¹) during (a, b) April–June and (c, d) July–September. Shadings represent terrain height (km). The blue circles represent the high occurrence-frequencies of HR.
FIGURE 3  Composite specific humidity (shaded, $10^7$ g kg$^{-1}$) and moisture convergence (contour with negative values, $10^{-7}$ kg kg$^{-1}$ m s$^{-1}$) of (a, c) HR-type and (b, d) no-HR-type at 925 hPa at 1800 UTC during (a, b) April–June and (c, d) July–September. The gray shading represents topography.

FIGURE 4  Distribution of average surface winds at $-3$ hr (3 hr before the occurrence-time of HR) by (a, c) daytime and (b, d) nocturnal HR during (a, b) April–June and (c, d) July–September, the red vectors denote southerly wind and the blue vectors denote northerly wind. Shadings represent terrain height (km).
exhibited general eastward movement over South China. The average moving-speed of HR was 59 km\(\text{hr}^{-1}\). Note that the diurnal variation of the rainfall over South China exhibited two peaks (one in the early morning and the other in the late afternoon, Zhang and Zhai, 2011; Jiang et al., 2017; Chen et al., 2018; Zhong and Chen, 2020), the characteristics of the surface observations by daytime and nocturnal HR were separately examined in this study.

For the daytime HR, it exhibited more episodes and faster moving-speed than the nocturnal HR. Besides, the HR moving speed during July–September showed generally faster moving-speed and exhibited relatively fewer occurrence-frequencies of HR than that in April–June (Figure 2). The locations of high occurrence-frequencies of daytime and nocturnal HR were mainly located over the coastal areas and the north of Guangxi as well as the PRD region, which exhibited general east and southeast moving (66% of total HR) especially during April–June, as well as irregular moving directions during July–September. The general slower movement of HR during the pre-summer rainy season may relate to the quasi-stationary mesoscale vortex (Ge et al., 2011) and the quasi-stationary front over south China (Du and Chen, 2019).

For the large-scale environment of HR, the composite analysis showed that the specific humidity was generally higher than non-HR events (Figure 3). Besides, the low-level southerly wind and moisture convergence with HR episodes were generally stronger than that in the non-HR events, especially during July–September. However, the wind speed with no-HR episodes over Guangxi was generally stronger than that in the HR events during April–June, which implied that in addition to the low-level southerly wind, other impact factors including humidity, orographic distribution (Chen et al., 2018; Zhong et al., 2019a) as well as surface temperature (see Figure 5) should be considered together as the key characterization parameter for the occurrence of HR.

For the surface winds at −3 hr, the daytime HR in the PRD region exhibited a significant early convergence belt between the southeasterly and northeasterly winds (Figure 4). The nocturnal HR exhibited an early signal of consistently enhanced southwesterly surface winds and a subsequent cyclonic wind pattern at the occurrence-time of the HR. For the nocturnal HR, the PRD region exhibited a strong increase of southerly wind and a strong decrease of surface potential temperature during the warm season (Figure 5). For the daytime HR, it showed little change of the surface potential temperature.
during April–June but exhibited a strong decrease of surface potential temperature as well as little change of the surface wind during July–September. Both the daytime and nocturnal HR exhibited southeasterly wind at the occurrence-time of HR during the warm season over the south of the PRD region (not shown).

In general, during the first warm season from April to June, both nocturnal HR and daytime HR over the PRD region were strongly influenced by the southerly wind. For the nocturnal HR, the key characterization parameter was the outbreak of the southerly wind and strong decreases in surface potential temperature. For the daytime HR, the key characterization parameter was the convergences between the northeasterly winds over the north part of the PRD region and the southeasterly winds. It was found that the convection was strongly influenced by the cold outflow boundaries from the previously convections in the warm-sector during the pre-summer rainy season (Wu and Luo, 2016; Zhong et al., 2019a) and land breeze due to nocturnal radiative cooling (Li et al., 2008; Yin et al., 2019). The cold outflow could be caused by the east and southeast moving of HR (Figure 1d and Figure 2a), which lead to the convergence with southerly winds and thereafter triggered the HR over the PRD region. During the second warm season from July to September, the key characterization parameter of HR was the outbreak of the southerly wind and strong decreases of surface potential temperature, especially for the daytime HR.

Both nocturnal HR and daytime HR over the PRD region were strongly influenced by the southerly wind during April–June, which showed a cyclonic wind pattern during the occurrence-time of nocturnal HR and a strong early convergence belt at ~3 hr of daytime HR in the PRD region. The key characterization parameter of nocturnal HR was the outbreak of the southerly wind and strong decreases of surface potential temperature. For the daytime HR, the key characterization parameter was the early convergences between the southeasterly winds and the northeasterly winds over the north part of the PRD region, which might be related to the cold outflow from the upstream east-moving convections. During the second warm season from July to September, the key characterization parameter of HR was the outbreak of the southerly wind and strong decreases of surface potential temperature, especially for the daytime HR.

4 | DISCUSSIONS AND CONCLUSIONS

In the present study, the environment and movement as well as the surface characteristics of HR over the PRD region were examined based on 5 years HR episodes collected from the surface observations in South China during the warm season from 2015 to 2019. To clarify the characteristics and early signals associated with HR, an impact radius was introduced as the threshold of the composite analyses. The results show that the HR centers were mainly located over the PRD region of Guangdong and at the windward slope of the mountainous areas. Most HR exhibited general eastward movement over South China with an average moving-speed of 59 km·hr⁻¹. The daytime HR exhibited more episodes and faster moving-speed than the nocturnal HR. The specific humidity of HR was generally higher than non-HR events, and the low-level southerly wind with HR episodes was generally stronger than in the non-HR events during July–September. While the southerly wind with HR episodes was weaker than that of non-HR events over Guangxi Province during April–June.

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