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Statistical Characteristics of Pre-summer Rainfall over South China and Associated Synoptic Conditions

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Abstract

In this study, the climatological characteristics of pre-summer (April to June) rainfall over South China (SC) and the associated synoptic conditions are examined using 1980–2017 hourly rainfall observations and reanalysis data. The amount, frequency, and intensity of rainfall show pronounced regional variations and substantial changes between pre- and post-monsoon-onset periods. Owing to the more favorable thermodynamic conditions after monsoon onset over the South China Sea (SCS), rainfall intensifies generally over SC irrespective of the rainfall-event durations. Increased rainfall amounts in longer-duration (> 6 h) events were found over a designated west-inland region (west of 111°E), which are partially attributed to enhanced dynamic instability. In addition, rainfall events occur more frequently over the west-inland region, as well as coastal regions to the west of 118°E, but less over a designated east-inland region. Inland-region rainfall is closely linked to dynamic lifting driven by subtropical synoptic systems (low pressure and an associated front or shearline). The westward extension of the western North Pacific high and the eastward extension/movement of the front or shearline, interacting with the intra-period intensification of the southwesterly monsoonal flows, play important roles in providing high-θ_e (equivalent potential temperature) air to the west- and east-inland regions, respectively. Warm-sector coastal rain-
1. Introduction

South China (SC) generally refers to the region south of about 28°N and east of the Yungui Plateau (Fig. 1). Located in the East Asian monsoon region, SC features a long rainy season from April to early October (Ramage 1952). Owing to the frequent occurrence of heavy rainfall at hourly and longer time scales during the rainy season (Zheng et al. 2016), SC is exposed to high-risk of flash flooding and inundation (Hallegatte et al. 2013). In accordance with the subseasonal migration of the East Asian summer monsoon (EASM) circulation and rainfall (Ding 1994; Ding and Chan 2005), the rainy season in SC can be divided into early and late periods, with the demarcation between the two being the end of June (Yuan et al. 2010). The early period (April to June) is the pre-summer rainy season, occurring during the early stage of the EASM and accounting for about half of the annual rainfall amount (Luo 2017). Hence, an improved understanding of the regional variations in the characteristics of pre-summer rainfall over SC and the associated synoptic conditions is expected to advance our rainfall forecasting skill, which is important to the local society.

The pre-summer rainy season in SC covers two subperiods, referred to as the pre- and post-monsoon-onset periods, respectively (e.g., Jiang et al. 2017; Chen and Luo 2018). After the onset of the South China Sea (SCS) monsoon in mid-to-late May (Xie et al. 1998; Luo et al. 2013), heavy-rainfall events during the pre-summer rainy season tend to occur more frequently (Ding and Chan 2005) with notable changes in the paths and sources of moisture supplied to SC (Chen and Luo 2018). Quantitative comparisons of the statistical characteristics of pre-summer rainfall over SC between the pre- and post-monsoon-onset periods using multiple satellite products (Xu et al. 2009; Luo et al. 2013) suggest an increase in domain-averaged rainfall accumulation and a generally enhanced convective intensity after the SCS monsoon onset. However, extremely heavy rainfall exceeding 500 mm day$^{-1}$ or 180 mm h$^{-1}$ is also observed over SC even before the onset of the SCS monsoon (e.g., Wang et al. 2014; Huang et al. 2019).

The major large-scale weather systems governing pre-summer rainfall over SC include middle-high-latitude troughs and ridges, South Asian high-pressure systems, SCS monsoon surges, and subtropical highs centered over the Western Pacific Ocean (Ding 1994). It has long been known that pre-summer rainfall over SC often occurs in the warm sector of a surface baroclinic wave cyclone, a few hundred kilometers away from the cyclone front (Huang et al. 1986). Frontal rainfall and warm-sector rainfall may occur simultaneously in the form of dual rain belts or as a single rain belt over SC. Recent studies revealed that warm-sector rainfall is associated with boundary layer (BL) flows of tropical origins (Luo et al. 2017), surface heating and local topographic lifting (Jiang et al. 2017), mesoscale cold pools (Wu and Luo 2016), land/sea-breeze fronts (Chen et al. 2017), terrain effects (Wang et al. 2014; Tu et al. 2014), and urban heat island effects interacting with sea breezes (Wu et al. 2019). Heavy-rainfall case studies showed that the dual rain belts simultaneously observed over inland and coastal SC can be closely related to the coupling of a BL jet (BLJ) and a synoptic-system-related low-level jet (SLLJ) (Du and Chen 2018; 2019). However, a systematic analysis related to synoptic conditions for pre-summer rainfall over SC is still lacking. In particular, few studies compared synoptic conditions among the subregions of SC during the pre-summer rainy season, or between the pre- and post-monsoon-onset periods.

This study investigates the statistical characteristics
of pre-summer rainfall over SC and its associated synoptic conditions, with a focus on comparisons between inland and coastal regions, as well as between pre- and post-monsoon-onset periods. The next section describes the data and analysis methods. Section 3 compares the statistical characteristics of the rainfall events between the pre- and post-monsoon-onset periods of 1980–2017. The synoptic conditions on long-duration rainy days (the definition will be presented in Section 2.3) over the inland SC regions are discussed in Section 4. For long-duration rainy days over the coastal region that occur on their own or simultaneously with long-duration rainy days over the inland region, synoptic conditions are presented in Section 5, with an emphasis on the LLJs. Summary and conclusions are provided in Section 6.

2. Data and methods

2.1 Determination of the SCS monsoon onset

In this study, the onset time of the SCS summer monsoon was determined following the National Climate Center of China Meteorological Administration (CMA) (http://cmdp.ncc-cma.net/Monitoring/monsoon.php). It is the first pentad when the 850 hPa zonal wind steadily (for two pentads with a break at most one pentad, or last for more than two pentads continuously) changes from easterly to westerly and the 850 hPa equivalent potential temperature \( \theta_e \) is 340 K or greater averaged over the SCS area (10–20°N, 110–120°E). The pre-monsoon-onset period is defined as that from April 1 to the earlier half of the onset pentad, whereas the post-monsoon-onset period consists of the days from the later half of the onset pentad to June 30. Using the European Centre for Medium-Range Weather Forecasts Interim reanalysis dataset (ERA-Interim; Dee et al. 2011; https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim) with a horizontal resolution of 0.25° × 0.25°, the monsoon onset pentad is determined for each year of 1980–2017. The results suggest that the SCS monsoon onset occurs mostly in mid-to-late May, in agreement with previous studies (Xie et al. 1998; Luo et al. 2013). The earliest onset in this study occurs in the 24th pentad (26–30 April; 2012) and latest occurs in the 32nd pentad (6–10 June; 1987, 1989, 1991, 2004). The 1980–2017 pre- and post-monsoon-onset periods, respectively, are 49.6 and 41.4 days per year on average.

2.2 Definition of the rainfall events

The quality-controlled, long-term, gauge-based hourly rainfall dataset from the National Meteorological Information Center (NMIC) of CMA was used to investigate the statistical characteristics of pre-summer rainfall. A quality-control procedure has been applied to the dataset by the NMIC, consisting of a climatological limit value test, a station extreme value test, an internal consistency test, and a comparison with manually checked daily rainfall data. This dataset has been extensively used to investigate the characteristics of subdaily rainfall over China (e.g., Yu et al. 2007, 2013; Li et al. 2008, 2013; Luo et al. 2016). In the present study, we utilized 303 meteorological stations in SC (Fig. 1) that have continuous records from 1980 to 2017.

Three subregions in SC were selected with distinct topographical features and pre-summer rainfall properties, such as diurnal variations (Jiang et al. 2017) and convective intensity (Xu et al. 2009; Luo et al. 2013). These subregions are the west-inland, east-inland, and coastal regions (Fig. 1). The west-inland region is located to the east of the Yungui Plateau, covering most of Guangxi (GX) province and southeast Guizhou province. The east-inland region is a hilly region that includes north Guangdong (GD), southwest Fujian (FJ), south Jiangxi, and southeast Hunan. The coastal region mostly includes coastal GD and is relatively flat with small scattered hills.

A “rainfall event” is defined following Yu et al. (2007); a spell that has measurable rainfall (≥ 0.1 mm h\(^{-1}\)) without any or at most a 1 h interruption (Li et al. 2013; Yu et al. 2013). After a rainfall event begins, if its interruption lasts for 2 h, the rainfall that follows will belong to a new rainfall event. The duration of a rainfall event is the length of time between the beginning and the end of the event. According to their durations, rainfall events are classified into short-duration (1–6 h), moderate-duration (7–12 h), and long-duration (> 12 h) categories. For each rainfall-event type, the accumulated rainfall amount, occurrence frequency, and hourly rainfall intensity are comparatively analyzed for the pre- and post-monsoon-onset periods.

2.3 Analysis of the synoptic conditions

Occurrence of long-duration rainfall events simultaneously at a considerable fraction of stations over a region is expected to be associated with prominent synoptic-scale forcing (Holton 2004), whereas synoptic forcing is often weak for shorter-duration, local-scale rainfall in a region (Guo et al. 2017). In this study, a long-duration rainy day of a subregion is defined as a day (1200–1200 UTC) when at least 15% of the stations in the subregion experience a
long-duration rainfall event. If long-duration rainfall at a station spans 12 UTC, it is considered to belong to both days before and after for that station. By such a definition, rainfall events with short, moderate, and long durations may occur simultaneously over a subregion on a long-duration rainy day. Our analysis results indicate that the west-inland region experiences 246 and 303 long-duration rainy days, accounting for 13 % and 19 % of the 1980–2017 pre- and post-monsoon-onset periods, respectively. The numbers (percentages) of long-duration rainy days are 514 (27 %) and 338 (21 %) for the east-inland region and 316 (17 %) and 273 (17 %) for the coastal region. Concurrence of long-duration rainy days over the coastal subregion and the east-inland subregion is often observed, sometimes over the two inland subregions and occasionally over the three subregions (Fig. 2). These statistics further supplement those of previous case studies that revealed the existence of dual rain belts over coastal and inland SC during the pre-summer rainy season (Huang et al. 1986; Ding 1994; Du and Chen 2018; Liu et al. 2018).

In order to examine the synoptic-scale circulation and thermodynamic conditions on long-duration
rainy days over the selected subregions, composite and anomalous fields of relevant variables, such as horizontal and vertical winds, vertical vorticity, potential vorticity, $\theta_e$, and precipitable water (PW), were analyzed using ERA-Interim data. The composite fields of each variable were obtained by averaging all six-hourly fields of the variable on the long-duration rainy days for the selected subregion(s). The anomalous fields were calculated as composite minus the corresponding 1980–2017 climatology (i.e., averaged over all the six-hourly reanalysis data) during the pre- and post-monsoon-onset periods, respectively.

The presence and structure of LLJs were analyzed using ERA-Interim data, largely following the methods adopted by Du et al. (2014), to reveal their possible relation with pre-summer rainfall over the SC coast. The following criteria were used to identify LLJs: (1) the maximum wind speed in the lowest 13 layers (below approximately 4 km) is more than 10 m s$^{-1}$ with wind direction between 90° and 270° (southwesterly to southeasterly) and (2) the wind speed must decrease by at least 3 m s$^{-1}$ from the height of the wind maximum to the wind minimum above that level. These criteria are similar to those adopted by Du et al. (2012, 2014), Pham et al. (2008), and Whiteman et al. (1997). The height of the LLJs is defined as the height of the horizontal wind speed maxima where the LLJs occur. The LLJs are classified into BLJs (occurring approximately below the 1 km level) and SLLJs (occurring approximately between the 1 km and 4 km levels). It is possible for a BLJ and an SLLJ to occur at the same time with a double peak in the vertical profile of wind speed, although this does not occur very often. When a double peak occurs, both peaks are counted. Furthermore, SLLJs (BLJs) with grids less than 25 % (10 %) in the region (110–118°E, 18–27°N) (dashed box in Fig. 1) are removed.

Table 1. Statistics of presummer rainfall over South China during the pre- and post-monsoon-onset periods of 1980–2017. Numbers in brackets represent the change (%) relative to the pre-monsoon-onset period.

<table>
<thead>
<tr>
<th></th>
<th>Pre-monsoon-onset period</th>
<th>Post-monsoon-onset period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span of the period (day yr$^{-1}$)</td>
<td>49.6</td>
<td>41.4 [−16.5 %]</td>
</tr>
<tr>
<td>Accumulated rainfall amount (mm yr$^{-1}$)</td>
<td>277.1</td>
<td>300.2 [+8.3 %]</td>
</tr>
<tr>
<td>Occurrence frequency of rainfall event (# yr$^{-1}$)</td>
<td>35.5</td>
<td>31.1 [−12.4 %]</td>
</tr>
<tr>
<td>Daily rainfall amount (mm)</td>
<td>5.6</td>
<td>7.3 [+30.4 %]</td>
</tr>
<tr>
<td>Daily occurrence frequency of rainfall event (#)</td>
<td>0.72</td>
<td>0.75 [+4.2 %]</td>
</tr>
<tr>
<td>Average duration of rainfall event (hour)</td>
<td>4.3</td>
<td>4.2 [+2.3 %]</td>
</tr>
<tr>
<td>Average intensity of hourly rainfall (mm h$^{-1}$)</td>
<td>1.81</td>
<td>2.29 [+26.5 %]</td>
</tr>
</tbody>
</table>

3. Amount, occurrence frequency, and intensity of rainfall events

3.1 Domain-averaged statistics

The SC domain-averaged rainfall statistics in 1980–2017 are shown in Table 1. Compared to the pre-monsoon-onset period, the rainfall amount accumulated during the post-monsoon-onset period increased by 8.3 % despite its shorter span (41.4 versus 49.6 days per year) and smaller number of rainfall events (31.1 versus 35.5 per station per year). The daily-averaged rainfall amount shows a substantial increase (30.4 %) after the SCS monsoon onset, whereas the occurrence frequency of the rainfall events increases slightly (4.2 %) and their hourly rainfall intensity is enhanced by 26.5 %. These results are mainly attributed to more favorable thermodynamic conditions for rainfall production over SC, that is, the higher convective available potential energy and larger amount of PW (Luo et al. 2013). The average duration of rainfall events decreases slightly (from 4.3 to 4.2 h) because of the large number of short-duration rainfall events in the post-monsoon-onset period (Fig. 3b).

Figure 3 shows the statistics of rainfall amount, occurrence frequency, and average rainfall intensity for the three rainfall-event types classified according to their duration. The short-duration type produces a larger amount of rainfall accumulation over SC compared to the other two types with longer durations (Fig. 3a), because of its substantially larger population (roughly four to five times greater than the moderate-duration event) in each period (Fig. 3b). Compared to the pre-monsoon-onset period, all three types have larger rainfall amounts during the post-monsoon-onset period (Fig. 3a). The largest increase in rainfall amount among the three types is observed in the long-duration type, with its median and maximal values among stations increasing by about 61 % and 58 %, respectively. Increasing ratios of the moderate-
duration type are the lowest (10% and 26%) among the three rainfall-event types, with those of the short-duration type in between (19% and 30%). After the SCS monsoon onset, the occurrence frequency increases for the short-duration type but remains about the same for the longer-duration types (Fig. 3b), whereas the average hourly rainfall intensity of all types is strengthened, especially the long-duration type (Fig. 3c).

In short, after the SCS monsoon onset, all three rainfall-event types over SC possess an enhanced hourly rainfall intensity particularly for the long-duration type. The occurrence frequency of the short-duration rainfall events increases, which can be attributed to the more frequent occurrence of thermally driven local-scale rainfall occurring in the afternoon (Dai et al. 1999; Luo et al. 2016). These changes can also be attributed to the more favorable thermodynamic and moisture conditions over SC.

3.2 Regional variations

The range and distribution of the rainfall amounts and intensities at individual stations over SC are presented in Fig. 4. Histograms and cumulative distribution functions (CDFs) of the rainfall amounts during the pre- and post-monsoon-onset periods, respectively, are shown in Figs. 4a and 4b. An examination of the rainfall amount histograms suggests that the fraction of stations with light rainfall (< 5 mm day$^{-1}$) decreases substantially from about 32.7% to 1.3%, whereas that of stations with heavier rainfall (> 10 mm day$^{-1}$) increases from 1.3% to 11.2% after the SCS monsoon onset. The spatial distribution of the rainfall amount during the pre-monsoon-onset period shows three areas of large rainfall amounts (about 10 mm day$^{-1}$) in central GD, coastal southwest GD, and northeast GX (Fig. 4c). After the SCS monsoon onset, central and costal GD and northeast GX tend to have larger rainfall amounts (about 12.5 mm day$^{-1}$) relative to other places in SC (Fig. 4d). The differences (post- minus pre-monsoon-onset period) in the rainfall amount (Fig. 4e) are positive at most stations except for some stations over the east-inland region. The largest increase (> 5 mm day$^{-1}$) in the rainfall amount is observed in the west-inland and coastal regions.

The histograms of the occurrence frequency of the rainfall events suggest that the frequency at the stations ranges from 0.2 to 1.1 events per day during both periods (Figs. 5a, b). The value exceeding 1.0 is the result of one station having a larger number of rainfall events compared to the number of days during each period. Stations with a low rainfall-event frequency
(< 0.6 events per day) account for 19 % of the population (Fig. 5a) and are located mostly in the west-inland and coastal regions in the pre-monsoon-onset period (Fig. 5c). In contrast, such stations only account for 6 % of the population (Fig. 5b) and are scattered over north and southwest of SC in the post-monsoon-onset period (Fig. 5d). The spatial distribution of the difference in the occurrence frequency shows an overall decrease over the east-inland region and a contrasting increase over the west-inland and coastal regions after the monsoon onset (Fig. 5e). The former is contributed by the lower occurrence of the three types of rainfall
events over the northern portion of the east-inland region (approximately north of 25°N), whereas the latter is contributed mainly by the greater occurrence of the short-duration rainfall events (Fig. 6). The relatively more frequent rainfall events over the northern portion of the east-inland region before the SCS monsoon onset are closely related to the persistent rainfall south of the Yangtze River (112–120°E, 25–30°N) in the spring (mid-March to early May) (Tian and Yasunari 1998; Zhao et al. 2008; Huang et al. 2015; Luo et al. 2016). The formation of such persistent rainfall in the spring is attributed to the moisture convergence and upward motion as a result of both the retarding and the deflecting effects of the TP on the westerlies (Wu et al. 2007) and the thermal contrast between western China and the subtropical western Pacific (Zhao, P. et al. 2007).

As is the case for the rainfall amount CDFs (Figs. 4a, b), the rainfall intensity CDFs also shift toward larger values in the post-monsoon-onset period (Figs. 7a, b), reflecting a general enhancement of rainfall intensity at the stations and consistent with Fig. 3c.
The spatial distributions present a strong dependence of rainfall strength on the latitude (i.e., more intense at lower latitudes) during both periods (Figs. 7c, d). The areas of strong rainfall intensity in GD and GX largely correspond to the frequent occurrence of convective precipitation features observed by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) (Kummerow et al. 1998) shown by Luo et al. (2013). In contrast, the weaker rainfall intensity over northern SC has a high (low) occurrence frequency of nonconvective (convective) precipitation features observed by the TRMM PR (Luo et al. 2013). The differences in the rainfall intensity between the post- and pre-monsoon-onset periods (post- minus pre-monsoon-onset period) are positive at almost all stations, with relatively larger increases in the west-inland region (Fig. 7e) mainly contributed by the intensification of longer-duration events (not shown).

In summary, after the SCS monsoon onset, hourly rainfall intensities of rainfall events are generally strengthened over SC, especially the longer-duration (> 6 h) events over the west-inland region. All three types of rainfall events, particularly the short-duration events, occur more frequently in the west-inland and coastal regions, but the rainfall events occur less frequently over the northern portion of the east-inland region during the post-monsoon-onset period. As a result, a substantial increase in accumulated rainfall amounts is observed in the west-inland and coastal regions during the post-monsoon-onset period, whereas the rainfall amounts in the east-inland region during the two periods are nearly comparable.

4. Synoptic background on the inland long-duration rainy days

During the pre-monsoon-onset period of 1980–2017, 246 and 514 long-duration rainy days (definition given in Section 2.3) are found over the west- and...
east-inland subregions, respectively (Fig. 2). Among those days, 110 days are overlapping for the west- and east-inland regions (but not the coastal region). Similarly, 303 and 338 long-duration rainy days are found during the post-monsoon-onset period over the west- and east-inland subregions, respectively, including 88 days over both inland subregions (but not the coastal region). In order to better understand the thermodynamic and dynamic conditions under which the long-duration rainy events occur over the inland regions, this section presents the composite and anomalous fields on three groups of long-duration rainy days, namely, west-inland region only (first group), both inland regions (second group), and east-inland region only (third group), respectively.

4.1 The pre-monsoon-onset period

Similar patterns are found in the 850 hPa composite fields on the long-duration rainy days of the pre-monsoon-onset period over the west-inland region only
(88 days), both inland regions (110 days), and east-inland region only (209 days) (Figs. 8a–c). The 850 hPa geopotential height ($H_\theta$) field shows a low pressure near the west-inland region and a high pressure over the western North Pacific. A southwest-northeast-oriented shearline extends from the west-inland region toward central east China. Along this shearline, a sign change in $\partial PV/\partial y$ (where $PV$ is the potential vorticity) is observed (the layer of reversed PV gradient reaches about 800 hPa, not shown), suggesting that the Charney–Stern instability criterion (Charney and Stern 1962) is satisfied there. Large southward gradients of $\theta_e$ and large standard deviations of meridional wind ($\nu$) are found in the northern portion of the inland regions, being more prominent in the west-inland region. The anomalous fields (Figs. 8d–f) reveal the presence of northeasterly wind anomalies, (although being less evident for the long-duration rainfall days over the west-inland region only; Fig. 8d), negative $\theta_e$ anomalies to the north of the inland regions, and cyclonic vorticity anomalies around the shearline.

All these features collectively reveal a close association between the inland rainfall and subtropical synoptic systems (low pressure and associated fronts, shearlines, and vortices) (Huang et al. 1986; Ding 1994). The convergence of the southerly and northerly winds results in the formation of a boundary between the warm moist air and cold dry air, leading to an upward motion within a deep moist unstable layer (Zhao, S. X. et al. 2007). The cyclonic vorticity anomalies (Figs. 8d–f) can be traced back to the migratory cyclonic anomalies that originated near the southeastern margin of the Tibetan Plateau a few days earlier (Li et al. 2014; Huang et al. 2018), or are closely related to a deep trough anomaly extending from an intense cyclonic anomaly over north China, which in turn could be traced back to a midlatitude Rossby wave train passing the Tibetan Plateau (Huang et al. 2018).

Differences among the three inland-rainfall groups during the pre-monsoon-onset period are primarily detectable in the wind fields. Specifically, the first group (long-duration rainfall days over the west-inland region only) is characterized by strong southerly flow prevailing over the west-inland region and its immediate upstream regions (Fig. 8a). The second group (long-duration rainfall days over both inland regions) exhibits strong westerly flow to influence the east-inland region, in addition to the southerly flow to the west (Fig. 8b). In the third group (long-duration rainfall days over the east-inland region only), the strong southwesterly flow possesses a larger zonal velocity component, mainly covering the east-inland region and its upstream regions (Fig. 8c). Meanwhile, a moist tongue (represented by PW) extends from north SCS and Gulf of Tonkin to the south boundary of the west-inland region in the first group; it broadens eastward to cover the immediate upstream portions of both west- and east-inland regions in the other two groups (Figs. 8a–c). Moreover, the western North Pacific high (WNPH) extends westward (retreats eastward) when rainfall is produced over the west-inland (east-inland) region. The easterly flows (and anomalies; Fig. 8d) prevail over northern SCS and change to southerly when approaching SC in the first and second groups, suggesting that the WNPH extends westward to persistently transport moisture (Chen and Luo 2018) and provide air masses with higher $\theta_e$ toward the west-inland region. In contrast, southwesterly flows (and anomalies; Fig. 8f) are observed over and upstream of the east-inland region in the third group, suggesting a crucial role played by the intra-period intensification of the southwesterly flows on providing higher-$\theta_e$ air to the east-inland rainfall. The intensification of the southwesterly flows over the SCS may be attributed to the enhancement of the pressure gradient force between an eastward-moving low pressure from western China and a westward-moving high pressure from the western North Pacific, as found by Zhao et al. (2003) using gridded data in the spring and summer of 1998 from the South China Sea Monsoon Experiment (SCSMEX; Lau et al. 2000).

4.2 The post-monsoon-onset period

A clear signature of the above-mentioned synoptic systems is also observed on the inland long-duration rainy days of the post-monsoon-onset period (Fig. 9). The differences among the three inland-rainfall groups during the post-monsoon-onset period can be seen in the wind and moisture fields (Figs. 9a–c). In the first group, the southwesterly flows extend from the northeast of the Indochina Peninsula to the western portion of SC, while the northern SCS is mainly influenced by weaker southerlies. In the second group, southwesterly flow prevails over a wider area to influence the eastern portion of SC. In the third group, the northern SCS and east-inland SC are impacted by strong southwesterly flows. Meanwhile, the moist area extending from the SCS and Gulf of Tonkin mainly influences the west-inland region in the first group; it expands eastward to cover the east-inland region in the other two groups. These differences among the three inland-rainfall groups during the post-monsoon-onset period are at least qualitatively consistent with those during the pre-monsoon-onset period. The differences among
Fig. 8.  (a–c) Composite fields at 850 hPa averaged on the long-duration rainy days over (a) only the west-inland region, (b) both the west- and the east-inland regions, and (c) only the east-inland region during the pre-monsoon-onset period: equivalent potential temperature ($\theta_e$, green solid, contoured at intervals of 4 K), geopotential height (black solid, contoured at intervals of 10 gpm), horizontal winds (vectors; red denotes wind speed ≥ 5 m s$^{-1}$), and precipitable water (PW, mm, blue shadings). The regions are outlined by pink quadrilaterals. The orange lines indicate the shearlines in the average wind fields, and the red contours represent the standard deviation of meridional velocity ($v$). (d–f) Anomalous fields of 850 hPa $\theta_e$ (green solid, contoured at intervals of 1 K), relative vorticity (red solid, 10$^{-6}$ s$^{-1}$), horizontal winds (vectors), and PW (mm, blue shadings) during the pre-monsoon-onset period corresponding to (a), (b), and (c), respectively. Anomalies are calculated as the averages on the long-duration rainy days over the inland region(s) minus the climatological (1980–2017) averages during the pre-monsoon-onset period, that is, averages over all six-hourly reanalysis data during the pre-monsoon-onset periods of 1980–2017.
the three groups (Figs. 8a–c, 9a–c) reflect the notion that the southeastward- or eastward-moving low-level vortices and associated shearlines or fronts, along with the westward-expanding WNPH (not shown), sequentially or simultaneously produce rainfall over the west- and east-inland SC. Such migratory synoptic systems are documented in case studies of pre-summer heavy rainfall over SC (e.g., Zhao et al. 2003; Du and Chen 2018; Zhang and Meng 2018).

Several differences in spatial patterns are apparent between the pre- and post-monsoon-onset periods (cf. Figs. 8, 9). The southwesterly air flow strengthens significantly over SC and its upstream after the SCS monsoon onset, consistent with the increased gradients in the $H_g$ field (cf. Figs. 9a–c, 8a–c). PW increases substantially over SC and north SCS, and $\theta_e$ generally becomes much higher (e.g., from 328–340 K to 344–352 K over the west-inland region). Correspondingly, the relative vorticity anomalies, which center in the west-inland region and extend toward

Fig. 9. As in Fig. 8 but during the post-monsoon-onset period.
the northeast, also have greater positive values during the post-monsoon-onset period. All these differences between the two periods collectively suggest more favorable thermodynamic conditions and dynamic instability for producing a stronger rainfall intensity over the inland regions after the SCS monsoon onset.

5. Synoptic background on the coastal long-duration rainy days

During the 1980–2017 pre-summer rainy season, 316 and 273 long-duration rainy days are found over the coastal region of SC during the pre- and post-monsoon-onset periods, respectively (Fig. 2). Among those days, 154 and 99 days have both coastal and east-inland regions (but not a west-inland region) as long-duration rainy days during the earlier and later periods, respectively. A concept of double LLJs (i.e., BLJ and SLLJ) and their relationship with the concurrent rain belts over inland and coastal SC has been recently proposed by Du and Chen (2018) on the basis of a heavy-rainfall case study. Their results suggested that inland frontal rainfall is closely related to SLLJ with maximum wind speed at 850–700 hPa, especially for the meridional wind component. Warm-sector heavy rainfall, a few hundred kilometers away from the front, is associated with a BLJ at 925 hPa. Du and Chen (2019) further demonstrated that the nighttime BLJ over the northern SCS strengthens the convergence at ~950 hPa near the coast where the BLJ’s northern terminus reaches the coastal terrain. Meanwhile, the SLLJ to the south of the inland cold front provides divergence at ~700 hPa near the SLLJ’s entrance region. Such low-level convergence and mid-level divergence together produce strong mesoscale lifting for convection initiation at the coast.

This section discusses the composite synoptic background of a large ensemble of long-duration rainy days in two groups: simultaneously over both coastal and east-inland regions (but not the west-inland region, the first group) and over the coastal region only (the second group). The BL on those long-duration rainy days during the pre-monsoon-onset period (Figs. 10a, b) is characterized by southerly air flow from the SCS to coastal SC that decelerates when approaching and crossing the SC coast. These results suggest the importance of the BL southerly flow over the northern SCS in producing coastal rainfall by providing high-$\theta_e$ air to the SC coast. Differences between the two groups are more obvious to the north of SC (cf. Figs. 10a, b). In the former group (i.e., with long-duration rainy days simultaneously over both the coastal and the east-inland regions), northeasterly flow prevails to the north of SC and penetrates to the west-inland region of SC, resulting in strong convergence over SC (red solid; Fig. 10a). Such northeasterly flow and the related convergence are greatly reduced in the latter group, that is, on the long-duration rainy days over the coastal region only (Fig. 10b).

The difference between the two groups indicates that the coastal rainfall is less associated with cold and dry air intrusion in the BL; instead, it is closely related to the deceleration of the southerly flow and associated convergence of BL high-$\theta_e$ air over the coast (Fig. 10b). At 850 hPa (Figs. 10c, d) southwestly flow passes sequentially over Hainan Island and the SC coastal region and further penetrates into the east-inland region with reduced speeds. The 850 hPa wind convergence at the northern terminus of the southwesterly flows is band-shaped and centered over the SC inland regions for both groups, with larger magnitudes in the first group (Figs. 10a, c). Over the coastal region the 850 hPa wind convergence is quite weak (Figs. 10c, d), in contrast to the stronger convergence in the BL (Figs. 10a, b).

On those long-duration rainy days during the post-monsoon-onset period, extensive southwesterly flow in the BL and lower troposphere extends from the northeastern portion of Indochina Peninsula and dominates the northern SCS, Gulf of Tonkin, and SC (Fig. 11). Similar to the above-mentioned findings for the pre-monsoon-onset period, the SC coastal region is influenced by BL convergence mostly due to the deceleration of the southwesterly flow (Figs. 11a, b). No northeasterly flow is observed in the BL and lower troposphere in the latter group (Figs. 11b, d), although they exist several hundred kilometers away to the northwest in the former group (Figs. 11a, c). These horizontal analysis results imply that the double LLJs (Du and Chen 2018, 2019) may occur over SC and the northern SCS on the coastal long-duration rainy days before and after the SCS monsoon onset, with even stronger intensities and broader expanses of the LLJs during the post- compared to the pre-monsoon-onset period (cf. Figs. 10, 11).

Consistent with the horizontal analysis, vertical cross sections of winds along 112°E (the brown line in Fig. 10b) also support the possible existence of BLJ (SLLJ) over the ocean (land) on the long-duration rainy days of the coastal region (Figs. 12a, b, d, e). The entrance and exit of the LLJs are usually related to the horizontal divergence and convergence, respectively (Hastenrath 1985), although they also depend on the jet stream configurations (Keyser and Shapiro 1986). During both pre- and post-monsoon-onset pe-
periods, BL convergence clearly exists at the exit region of the likely BLJ, which is located near the coastline, with 850–700 hPa weak divergence aloft at the entrance of the likely SLLJ. After the SCS monsoon onset, the BL wind speeds substantially increase, with the jet cores located farther south. A more elevated layer of convergence and upward motion is evident in the SC inland region during both periods relatively less evident in the coastal-only cases after the monsoon onset, Fig. 12e), which is co-located with the exit region of the SLLJ (Figs. 12a, b, d). Such a signal of double LLJs on the coastal long-duration rainy days is at least qualitatively consistent with the finding of Du et al. (2018, 2019). Such a signal is absent on the days when rainfall is not observed over the coastal region (Figs. 12c, f). On these dry days of the coastal region, the north SCS features a much weaker southerly flow (even northerly flow south of 18°N) in the BL, whereas the SC coast is dominated by large-scale downward motion.

In order to better examine the relation between the LLJs and the SC coastal rainfall, the long-duration rainy days over both the coastal and the east-inland regions are separated into two subgroups: one with (the first subgroup) and one without (the second subgroup) at least one BLJ event (definition provided in Section 2.3). Their vertical cross sections are shown in Fig. 13. The above-mentioned major features of relevance to the coastal rainfall occurrence (i.e., BL convergence coupled with divergence aloft over the coast) are observed in the first subgroup during both periods (Figs. 13a, b) and the second subgroup before the monsoon-onset (Fig. 13c). The results indicate that the double LLJs could play an important role in coast-
al rainfall, even if their wind speeds do not satisfy the criteria used to identify the BLJ and SLLJ events. The low-to-mid-level divergence over the coast has relatively smaller values compared to the BL convergence, especially on the days without the BLJ event during the post-monsoon-onset period (Fig. 13d). This indicates that the BL convergence probably plays a key role in the occurrence of coastal rainfall, whereas the divergence aloft can make some contribution. Moreover, recent studies suggested that the SC coastal rainfall can be closely associated with land/sea-breeze fronts (Chen et al. 2016), coastal mountains (Wang et al. 2014), and convectively-generated cold pools (Wu and Luo 2016; Liu et al. 2018). Heavy coastal rainfall could occur even without LLJs from the tropical ocean, such as the extreme rainfall event (maximal accumulative rainfall of 451 mm in 19h) over the western coastal region of Guangdong on 10 May 2013 (Wang et al. 2014).

It is noteworthy that the lower-level (about 850 hPa) horizontal winds tend to be stronger when the BLJ events are identified on the coastal rainy days, irrespective of whether the inland rainfall is simultaneously produced (Figs. 13, 14). This analysis suggests that the strength of the BLJ over the northern SCS is closely related to the synoptic systems over SC (low pressure, front, and shearline) and the WNPH, as noted in the case study by Du and Chen (2018). On the long-duration rainy days over both the coastal and the east-inland regions, the SLLJ collides with the northerly, cold, dry air flow (Fig. 13), providing strong synoptic forcing over the inland regions. In contrast, the BLJ’s northern terminus is located several hundred kilometers away from the northerly air flow, implying that local coastal processes (frictional convergence and orographic effects) rather than synoptic lifting dominate rainfall production. When only the coastal region experiences long-duration rainfall events, no strong synoptic forcing associated with northerly, cold, dry air flows is found near the coast (Fig. 14). This difference in the forcing mechanisms may explain the lower predictability of the pre-summer heavy rainfall over the SC coast compared to the inland regions (Huang and Luo 2017).

Fig. 11. As in Fig. 10 but during the post-monsoon-onset period.
6. Summary and conclusions

In this study, the statistical characteristics of the rainfall events over the inland and coastal subregions of SC (Fig. 1) during the pre- and post-monsoon-onset periods of the pre-summer rainy season were compared and analyzed in relation to their associated large-scale circulations. A rainfall event is defined as a period having measurable rainfall (more than 0.1 mm h⁻¹) without any or at most a 1 h interruption. A long-duration rainy day of a designated subregion is defined as a day when at least 15% of the stations in the subregion experience a long-duration (> 12 h) rainfall event. The pre-monsoon-onset period of each year covers the days from April 1 to the SCS monsoon onset, whereas the post-monsoon-onset period starts from the SCS monsoon onset to June 30. The principal findings of this paper are as follows.

(1) The 1980–2017 pre- and post-monsoon-onset periods consist of 49.6 and 41.4 days per year on average, respectively. Under the more favorable thermodynamic and moisture conditions over SC after the SCS monsoon onset, the daily rainfall amount and period-accumulated rainfall amount
increase by 30.4 % and 8.3 %, respectively. The hourly rainfall rate of the rainfall events also intensifies by 26.5 %, whereas the events’ average duration (4.3 versus 4.2 h) becomes slightly shorter because of the increased population of short-duration (1–6 h) rainfall events after the SCS monsoon onset.

(2) After the SCS monsoon onset, the hourly rainfall intensities of the short-, moderate-, and long-duration events are all enhanced, with a more significant increase in the longer-duration (> 6 h) categories over the west-inland region. Compared to the pre-monsoon-onset period, rainfall events occur more (less) frequently over the west-inland and coastal regions (the northern portion of the east-inland region), resulting in a substantial increase (little change) in the total rainfall amounts after the monsoon onset over these two regions (east-inland region).

(3) The long-duration rainy days over the inland SC regions are closely linked to subtropical synoptic systems (i.e., low pressure and an associated front or shearline) and southwesterly air flow of tropical origin, which together provide favorable dynamic instability and thermodynamic conditions for rainfall production. The westward extension of the WNPH and the eastward extension/movement of the front/shearline, interacting with the intraperiod intensification of the southwesterly monsoonal flows, play important roles in providing high-$\theta_e$ air to the west- and east-inland regions, respectively.

(4) About 64 % of the coastal long-duration rainy days are concurrent with the inland long-duration rainy days. Warm-sector coastal rainfall is closely related to the deceleration of the southerly BL flow over the northern SCS and the associated convergence of BL high-$\theta_e$ air near the coast. Coastal rainfall can also be aided by the SLLJ in the lower-
to-middle troposphere that provides divergence aloft with BL convergence near the coast.

In conclusion, this study provided a quantitative analysis of the characteristics of pre-summer rainfall over SC and the associated synoptic conditions. This 38-year statistical analysis not only supports but also expands upon previous studies showing qualitative results or focusing on a single heavy-rainfall case over SC. The properties of the double LLJs (BLJ, SLLJ) and their possible interactions, as well as their relationship with heavy rainfall over SC, deserve further investigations through more detailed analyses using observations and reanalysis data, combined with carefully designed numerical simulations.

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References


