Characteristics, Physical Mechanisms, and Prediction of Pre-summer Rainfall over South China: Research Progress during 2008–2019

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Abstract

The pre-summer rainy season (April to mid-June) over South China (SC) is characterized by a high intensity and frequent occurrence of heavy rainfall in the East Asian monsoon region. This review describes recent progress in the research related to this phenomenon. The mechanisms responsible for pre-summer rainfall consist of multiscale processes. Sea surface temperatures over the tropical Pacific and Indian Oceans are shown to have a great influence on the interannual variations of pre-summer rainfall over SC. Synoptic disturbances associated with regional extreme rainfall over SC are mainly related to cyclone- and trough-type anomalies. Surface sensible heating and mechanical forcing from the Tibetan Plateau can contribute to the formation and intensification of such anomalies. On a sub-daily scale, double rain belts often co-exist over SC. The northern rain belt is closely linked to dynamic lifting by a subtropical low pressure and its associated front/shear line, whereas westward extension of the western North Pacific high and intensification of the southwesterly monsoonal flows play important roles in providing high-equivalent potential temperature air to the west- and east-inland regions, respectively. The southern rain belt, with a smaller horizontal span, exists in the warm sector over either inland or coastal SC. The warm-sector rainfall over inland SC results from surface heating, local topographic lifting, and urban heat island effects interacting with the sea breeze. The warm-sector rainfall over coastal SC is closely associated with double low-level jets, land–sea-breeze fronts, and coastal mountains. A close relationship is found between convectively-generated quasi-stationary mesoscale outflow boundaries and continuous convective initiation in extreme rainfall events. Active warm-rain microphysical processes can play an important role in some extreme rainfall events,
although the relative contributions of warm-rain, riming, and ice-phase microphysical processes remain unclear. Moreover, to improve rainfall predictions, efforts have been made in convection-permitting modeling studies.

Keywords  East Asian summer monsoon; pre-summer rainfall over South China; multi-scale physical processes; convection-permitting modeling and prediction

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1. Introduction

South China (SC) generally refers to the region south of about 26°N and east of the Tibetan Plateau (TP) (Fig. 1). Located in the East Asian monsoon region, SC is one of the rainiest regions in the world, with the rainy season spanning from April to early October (Ramage 1952) and frequent intense rainfall occurring at hourly to longer time scales (Zheng et al. 2016). Therefore, SC is exposed to a high risk of flash flooding and inundation (Hallegatte et al. 2013). In accordance with the subseasonal migration of the East Asian summer monsoon circulation and precipitation (Tao and Chen 1987; Ding 1994; Ding and Chan 2005), the rainy season in SC can be divided into early and late periods, with the demarcation occurring at the end of June (Yuan et al. 2010). The early period from April to mid-June, i.e., the pre-summer rainy season (PSRS), occurs during the early stage of the East Asian summer monsoon and accounts for about a half of the annual precipitation amount (Luo et al. 2017). The PSRS ends when the monsoonal rain belt moves northward to the Yangtze River Valley in central East China in mid-June, i.e., when the Meiyu season starts.

During the past four decades, four scientific programs with field campaigns over SC have been carried out to study PSRS precipitation: the first program in 1977–1981 (Huang et al. 1986), the 1998 Heavy Rainfall Experiment in South China (HUAMEX) (Zhou et al. 2003), the Southern China Heavy Rainfall Experiment (SCHeREX) in 2008–2009 (Zhang et al. 2011; Ni et al. 2013), and the ongoing Southern China Monsoon Rainfall Experiment (SCMREX) (Luo et al. 2017). Results from these scientific programs have provided new insights into a wide range of phenomena and processes associated with PSRS precipitation, i.e., environmental characteristics at the synoptic and intermediate scales, topography, ocean–land contrast, mesoscale cyclones/shear lines/fronts, planetary boundary-layer processes, and mesoscale convective systems (MCSs) (Table 1). In addition to advancing the scientific understanding of PSRS precipitation, these scientific experiments have promoted the utilization of newly-developed remote sensors in field campaigns, the development of algorithms to derive meteorological parameters from remote-sensing observations, and the development of numerical weather prediction (NWP) techniques to improve PSRS rainfall forecasts. The scientific achievements of the previous three programs were summarized by Luo (2017); moreover, some details of the early stage (2013–2015) of SCMREX can be found in Luo et al. (2017).

This paper reviews recent (since approximately 2008) research progress on the characteristics, physical mechanisms, and prediction of PSRS precipitation over SC. Section 2 describes the overall climatological features of PSRS precipitation. Section 3 focuses on multiscale physical processes that are closely related to PSRS precipitation, particularly heavy rainfall. Section 4 describes relevant NWP studies on data assimilation impacts, improvements in model-physics parameterization, and development of ensemble forecasting techniques. The final section provides concluding remarks, including recommendations for future research topics.

2. Climatology of precipitation

2.1 Average rainfall distribution

The accumulated PSRS precipitation distribution exhibits a large spatial inhomogeneity with major rainfall centers located over the coastal areas of Guangdong and Guangxi provinces, central Guangdong, and northern Guangxi (Fig. 1a). Rainfall rates of > 50 mm day$^{-1}$ significantly contribute (more than 50%) to total rainfall amounts over these regions (Luo et al. 2013). These rainfall maxima mainly result from frontal and warm-sector rainfall processes (Huang et al. 1986; Liu et al. 2019). In contrast, tropical cyclones mainly contribute to heavy rainfall during the following season, i.e., July–September (Ramage 1952).
Other potentially important local factors will be discussed in the following sections.

The onset of the South China Sea (SCS) summer monsoon, made prominent by the firm establishment of 850-hPa southwesterly flow over the central SCS, generally takes place in mid–late May (Wang et al. 2004). Therefore, the PSRS consists of two sub-periods: the pre-monsoon-onset period (from April 1 to the SCS monsoon onset, or one month prior to the SCS monsoon onset) and the post-monsoon-onset period (from the SCS monsoon onset to June 31, or one month after the SCS monsoon onset). Details of the atmospheric circulation patterns and characteristics of these two sub-periods have been discussed in many previous studies. Interested readers should consult reviews such as that of Ding and Chan (2005). Various changes have also been found between the two sub-periods in terms of rainfall intensities, rainfall distributions, convective properties, and diurnal cycles of rainfall over SC (Xu et al. 2009; Luo et al. 2013; Jiang et al. 2017; Li et al. 2020). Therefore, the pre- and post-monsoon-onset periods of the PSRS are sometimes discussed separately in this review.

A 13-yr statistical study (Luo et al. 2013) shows that the regional average rainfall amount in the monsoon period of the PSRS (300 mm) is about 1.5 times that in the one-month period prior to the SCS monsoon onset (203 mm). This increased rainfall amount partly benefits from generally enhanced rainfall intensity over the entire SC after the SCS monsoon onset (Li et al. 2020). In particular, heavy rainfall (> 50 mm d\(^{-1}\)) accounts for about half of the precipitation of the rainfall maxima in coastal and central Guangdong and northeastern Guangxi during the monsoon period (Luo et al. 2013). Most precipitation during the PSRS is of a convective nature with mesoscale organizational characteristics (Xu et al. 2009). Moreover, the convective intensity (as suggested by most convection proxies, except lightning flash rate) is clearly enhanced.
after the SCS monsoon onset. Recent statistical analyses using gauge observations for the 1980–2017 PSRS (Li 2019; Li et al. 2020) indicate that after the SCS monsoon onset, hourly rainfall intensities of the rainfall events are enhanced irrespective of their durations, with more significant increases in the longer-duration (> 6 h) types over the west-inland region (Fig. 1). Compared with the pre-monsoon-onset period, the rainfall events occur more frequently over the west-inland and coastal regions but less frequently over the east-inland region, resulting in substantial increases in rainfall amounts over the west-inland and coastal regions but little change over the east-inland region (Li et al. 2020). The relatively more (less) frequent rainfall events over the east-inland region before (after) the SCS monsoon onset are closely related to the spring (mid-March to early May) persistent rainfall south of the Yangtze River (112–120°E, 25–30°N) (Tian and Yasunari 1998; Zhao et al. 2008; Huang et al. 2015; Luo et al. 2016). The formation of such persistent rainfall in spring is attributed to moisture convergence and upward motion as a result of the retarding and deflecting effects of the TP on westerlies (Wu et al. 2007) as well as the thermal contrast between western China and the subtropical western Pacific (Zhao et al. 2007).

Daily rainbands with a west–southwest to east–northeast orientation (i.e., for which the horizontal inclination is often < 30°) are a distinct rainfall distribution feature over SC during the post-monsoon-onset period of PSRS (Xu et al. 2009; Luo et al. 2013). The formation of such daily rainbands is closely related to a quasi-stationary front or 850-hPa shear line. Most of the rainbands originate between 25° and 30°N and propagate southeastward before becoming quasi-stationary in their late stage (Fig. 2). On average, they exhibit a 4–5-day lifespan, although in some extreme cases, they could persist for more than 10 days (Xu et al. 2009). The distribution of accumulated rainfall during PSRS days with the abovementioned rainbands presents a similar pattern to that of the rainfall accumulated during the entire PSRS. In contrast, the days without such rainbands during the post-monsoon-onset period of PSRS have only a weaker rainfall center in northeastern Guangxi (Xu et al. 2009). This indicates that the rainbands and the associated synoptic systems contribute substantially to the total PSRS precipitation.

The distribution of sub-daily rainfall over SC during the PSRS often exhibits a phenomenon of coexisting double rain belts (Huang and Luo 2017; Du and Chen 2018). The northern rain belt, located over the inland regions of SC, is closely linked to dynamic lifting by subtropical synoptic systems (low pressure and associated front/shear line), whereas the westward extension of the western Pacific subtropical high (WPSH) and the intra-period intensification of the southwesterly monsoon flows play important roles in providing high-$\theta_e$ air to the west- and east-inland regions, respectively (Li et al. 2020). The southern rain belt is typically located 200–300 kilometers south of the north rain belt in the warm sector over either inland or coastal SC, with a smaller horizontal span than that of the northern rain belt. The warm-sector rainfall over inland SC is a result of surface heating and local topographic lifting (Jiang et al. 2017) and an urban heat island effect interacting with the sea breeze (Wu et al. 2019). On the other hand, that over coastal SC is closely associated with low-level jets (LLJs) (Du and Chen 2018, 2019), land–sea-breeze fronts (Chen et al. 2017), coastal mountains (Wang et al. 2014), and convectively-generated cold pools (Wu and Luo 2016; Liu et al. 2018).

### 2.2 Diurnal variations in rainfall

Rainfall amount, frequency, and intensity over SC during the PSRS exhibit pronounced diurnal variations, with substantially different amplitudes from the western to eastern and inland to coastal regions of SC (e.g., Chen et al. 2009a; Jiang et al. 2017). The western region of SC often encounters significant nocturnal-to-morning rainfall under the influence of enhanced nocturnal low-level southwesterly winds.
Rainfall over this region presents an eastward- or southeastward-propagating mode (Fig. 3), which is associated with enhanced transport of warm and moist air of tropical origin and induced low-level convergence. In contrast, the inland area of the eastern region of SC is dominated by afternoon rainfall (Fig. 3), as a response to the thermal instability and moist static energy induced by daytime solar radiation and topographic inhomogeneity (Chen et al. 2018).

Rainfall over the southeastern coastal regions of SC also presents pronounced diurnal cycles. However, these are more complicated than those of the inland region owing to the complex coastal terrain distribution and diverse ambient low-level airflows (Chen, X. et al. 2014, 2016, 2017; Jiang et al. 2017; Chen et al. 2018; Du and Rotunno 2018). Specifically, an inland propagation of rainfall occurs from noon to afternoon in association with sea breezes; this is more apparent during days with weak low-level southerlies than it is during high-wind days as the land–sea temperature contrast is stronger on low-wind days, leading to a stronger sea-breeze. In addition, it is more evident in the post-monsoon-onset period owing to the appearance of stronger onshore winds in the afternoon, which result from stronger solar heating as compared with that of the pre-monsoon-onset period. During evening to morning hours, an offshore rainfall line parallel to the coastline propagates to the open sea because of the convergence between onshore monsoonal winds and land breezes. In addition, the mountain breeze produced by coastal terrain can merge with the land breeze. These propagation modes that are perpendicular to costal lines can be accelerated by cold pools induced by latent cooling and slowed by coastal mountains. Using Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) simulations, Du and Rotunno (2018) illustrated that vertically-integrated vertical vapor advection plays a key role in connecting rainfall and wind in the diurnal cycle. Using a two-dimensional linear land–sea breeze model with a background wind, they further demonstrated that in terms of speed and phase, the two propagating modes (onshore and offshore) are associated with inertia-gravity waves. The background wind changes the pattern of the inertia-gravity waves and further affects the diurnal propagation.

The various diurnal variations jointly cause a double peak structure of precipitation over the entire SC, one in the late afternoon and one in the early morning (Fig. 4; Jiang et al. 2017). The two peaks have different characteristics before and after the onset of the monsoon. For example, during the pre-monsoon-onset period, the morning peaks are stronger than the late afternoon peaks in terms of rainfall amount and frequency. In contrast, during the post-monsoon-onset period, the two rainfall amount peaks are almost equal. However, the late afternoon has a much higher
rainfall frequency peak, whereas the morning period has a much higher rainfall intensity.

If the coastal and inland regions over the eastern SC are considered separately, the rainfall structures would be different from those over the entire SC. For example, a statistical analysis by Chen et al. (2018) shows that during the pre-summer (May–June) season from 1998 to 2014, the morning rainfall peak was more pronounced over the SC coastal area, whereas afternoon and nocturnal rainfall were dominant on land and in the northern inland region, respectively. These different rainfall peak distributions are co-regulated by monsoon southwesterly winds, frontal activities, coastal mountains, and land–sea thermal contrasts. The monsoonal southwesterly winds over SC are also found to have significant daily changes, i.e., they attain maxima (minima) in the early morning (afternoon), which is strongly related to diurnal rainfall variations over SC (Chen, G. et al. 2009b, 2013; Li et al. 2018; Xue et al. 2018). Along with the change in monsoon activities, diurnal rainfall variations have exhibited long-term changes in past decades (Yuan et al. 2013; Chen, G. et al. 2014, 2018).

2.3 Extreme rainfall

a. Threshold of extreme rainfall

SC is an area that experiences frequent extreme rainfall during the East Asia summer monsoon season (Zheng et al. 2016; Luo et al. 2016). For example, an extremely high hourly rainfall rate of 184 mm h⁻¹ was recorded during a nocturnal rainfall event over the Pearl River delta on May 7, 2017 (Huang et al. 2019). Zheng et al. (2016) investigated the climatology of extreme rainfall over China in accumulated periods ranging from 1–24 h. They found that the maximum 50-yr (1981–2012) return value for hourly rainfall is ranging from 1–24 h. They found that the maximum extreme rainfall over China in accumulated periods were about 50.1, 59.5, and 59.9 mm h⁻¹, respectively. Meanwhile, the values at the 90th percentile are only 5.1, 7.1 and 8.1 mm h⁻¹, respectively. Thus, it seems appropriate to use an hourly rainfall rate of 60 mm h⁻¹ as the threshold for an extreme hourly rainfall (EXHR) record over SC during the PSRS (similar to the work by Chen, Y. (2018) and Li (2019)). This value is three times that of the definition for short-duration heavy rainfall in China (Zheng et al. 2016) and 40 % of the maximum 50-yr return value.

b. Distribution and synoptic analysis of EXHR

Using a gridded rainfall dataset (8 × 8 km) based on 3405 rain gauges over SC, Li (2019) examined the temporal and spatial distributions of extreme hourly rainfall (> 60 mm h⁻¹) in SC during the 2011–2017 PSRS, including a comparison between the pre- and post-monsoon-onset periods defined by Li et al. (2020). In total, there are 43 % and 57 % EXHR events during the pre- and post-monsoon onset periods (approximately 47 and 44 days yr⁻¹), respectively. The daily-averaged occurrence frequency of EXHR increases by about 40 % after the monsoon onset. In addition, the majority (approximately 80 %) of EXHR events in the former period occurred within 20 days before the onset of the SCS summer monsoon, suggesting a high correlation between EXHR over SC and monsoon. In terms of spatial distribution, the EXHR exhibits four centers of occurrence frequency, i.e., northwestern and southeastern regions of Guangxi and central and coastal regions of Guangdong. Before the monsoon onset, EXHR mainly occurs in northwestern Guangxi, central Guangdong, and the western-to-central coast of Guangdong. After the monsoon onset, EXHR occurrence frequency in northwestern and southern Guangxi and on the eastern coast of Guangdong increases significantly (cf. Figs. 5a, b).

By examining all the EXHR cases, the synoptic patterns favorable for EXHR production over SC (mostly covering Guangdong and Guangxi provinces) during the PSRS can be classified into four types, i.e., surface front, low-level shear line, low-level vortex, and warm-sector (or weak-gradient) (Li 2019) (Fig. 6). The first three types are associated with stronger synoptic forcing, as compared with the fourth type. For 2011–2017 EXHRs, the weak-gradient type is most significant, accounting for approximately 43 % and 35 % of the total EXHR populations during the pre- and post-monsoon-onset periods, respectively; this is followed by the surface front type (39 % and 34 %, respectively). The EXHRs in Guangdong are mainly of the fourth type (Figs. 5c, d), i.e., they are produced in an environment with weak gradients in both temperature and moisture and high values of equivalent poten-
tial temperature ($\theta_e$) in the lower troposphere (Fig. 6d), whereas those in Guangxi are closely related to synoptic surface fronts (Figs. 5e, f, 6a). Rainfall intensification contributes at least partly to the warm-sector type EXHRs over the Pearl River Delta in Guangdong as a result of the strong urban heat island effect interacting with sea breezes (Wu et al. 2019). The shear line- and vortex-type EXHRs have a higher occurrence frequency over Guangxi than they do over Guangdong, combining to account for 18% and 31% of the EXHR populations during the pre- and post-monsoon-onset periods, respectively (Figs. 5g–j, 6b, c). Note that the proportion of EXHR events induced by tropical cyclones is only about 1.0% over SC during the 2011–2017 PSRS.

The strength and pattern of the synoptic forcing has a significant impact on the organization modes of rainstorms in EXHR episodes (Chen, Y. 2018). In general,
for the EXHRs of the surface front, low-level shear line, and low-level vortex types, which are closely related to strong synoptic lifting, the rainstorms mostly appear as a quasi-linear mode. In contrast, for the weak gradient type occurring under an apparently weak synoptic lifting, the EXHR-producing storms tend to consist of multiple convective belts along the coast (e.g., Wang et al. 2014; Wu and Luo 2016; Liu et al. 2018) or exhibit scattered and small-scale structures over the inland region (Chen, Y. 2018).

3. Relation between heavy rainfall and multiscale processes

3.1 Influences of tropical oceans and TP

The sea surface temperature (SST) over tropical oceans greatly influences interannual variations in pre-summer rainfall over SC. A simultaneous presence of a colder-than-normal SST in the tropical western Pacific and warmer-than-normal SST in the tropical eastern Pacific would significantly weaken the back-

Fig. 6. Schematic diagrams of environmental conditions in the mid- and lower-troposphere at the time of the EXHR over SC during the PSRS, including four types: (a) surface front type, (b) low-level vortex type, (c) low-level shear line type, and (d) weak gradient type. Blue and green contours represent, respectively, the geopotential height \((H_g)\) and equivalent potential temperature \((\theta_e)\) at 850 hPa. “L” denotes the synoptic-scale low pressure center. Blue arrows denote 850-hPa horizontal winds. The thick blue line with double triangles in (a) represents the surface front. Thick brown lines in (b) and (c) denote shear lines at 850 hPa. Purple shading indicates where the 700-hPa ascent is maximized. Shadings in green, orange, and red represent radar reflectivities of roughly 20, 40, and 50 dBZ, respectively. Light blue shading south of the coastline (denoted by thick black line) indicates the South China Sea.
ground Walker circulation. The associated descending anomalies in the tropical western Pacific would suppress convection and excite an anomalous anticyclone near the Philippines in the lower troposphere (Gu et al. 2018) via the Matsuno–Gill-type Rossby wave response (Matsuno 1966; Gill 1980), leading to lower-tropospheric southwesterly wind anomalies. In addition to tropical Pacific SST, tropical Indian Ocean basin warming could also be closely related to pre-summer rainfall over SC (Yuan et al. 2019). The diabatic heating induced by Indian Ocean basin warming in late spring and summer can excite a warm atmospheric Kelvin wave along the Equator; the wave then propagates eastward to the tropical western Pacific. This results in surface convergence on the Equator and divergence in the off-equatorial regions, thereby resulting in an anomalous anticyclone in the SCS-western North Pacific (Xie et al. 2009, 2016; Chowdary et al. 2011). The related southwesterly anomalies transport more moisture to SC and lead to more moisture convergence and precipitation in this region. The teleconnections between the PSRS precipitation over SC and the Indian Ocean SST were previously well reproduced in sensitivity experiments using an atmospheric general circulation model (Yuan et al. 2019).

In addition to the tropical oceans, the TP plays an important role in affecting the pre-summer heavy rainfall over SC. A study using convection-permitting ensemble simulations of persistent heavy rainfall over SC (Li et al. 2014) suggests that the strong surface sensible heating over the TP could significantly affect the temperature distributions over the plateau and its surroundings. The thermal wind adjustment subsequently changes atmospheric circulations and relevant synoptic systems. In particular, the mid-level positive vorticity propagates downstream from the TP, enhancing the eastward-moving low-level cyclones and the associated southwesterly low-level jet (LLJ) south of the vortices, collectively leading to intensified precipitation over SC. Wan et al. (2017) demonstrated that lower soil moisture could enhance surface sensible heat fluxes and lead to a warmer and deeper boundary layer over the TP, which can intensify the high pressure anomaly downstream over the Yangtze Plain, thereby blocking northward movement of the low pressure and promoting more extreme rainfall over SC.

Earlier studies suggested that mechanical forcing (blocking and deflecting effects) by the TP can lead to the formation of cyclones in the lower troposphere around the Sichuan basin near the TP’s southeastern margin (Wu and Chen 1985; Kuo et al. 1986; Chang et al. 1998). Such cyclones, sometimes known as the southwest vortices, are known to be important rain producers not only for the Sichuan basin but also for eastern, southern, and even northern China after they have moved out of the basin (Tao and Ding 1981). A recent study consistently found that the synoptic-scale anomalous circulations of 24 extreme rainfall episodes over SC (defined as those with a daily rainfall amount in the top 5% during the 1998–2015 PSRS) mostly feature with cyclone- and trough-type anomalies (Huang et al. 2018). The cyclone-type anomalies could be traced back to the generation of cyclonic anomalies downstream of the TP a few days earlier. The production of extreme rainfall in the trough-type episodes is 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 by the TP.

3.2 Large-scale environments

a. Water vapor paths

After the onset of the SCS monsoon in mid-to-late May (Xie et al. 1998; Luo et al. 2013), the paths and sources of moisture supplied to SC change notably (Chen and Luo 2018). During the 1979—2014 pre-monsoon-onset period, the trajectories of air parcels can be clustered into six groups (Fig. 7a) using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al. 2015) (https://www.arl.noaa.gov/hysplit). Four of the paths originate over either the Bay of Bengal (Group 1), the SCS (Group 2), the western North Pacific (Group 3), or the East China Sea (Group 4). These paths, with an ocean origin, account for 83.9% of the total moisture over SC. The remaining two paths originate over either Lake Baikal (Group 5) or the Persian Gulf (Groups 6). The trajectories during the post-monsoon-onset period are clustered into four groups that originate over the Arabian Sea (Group 1), the central Indian Ocean (Group 2), the eastern Indian Ocean near Sumatra (Group 3), and the western North Pacific (Group 4) (Fig. 7b). After the SCS summer monsoon onset, the contribution of the Pacific-originating trajectories to the total moisture amount over SC decreases from about 46.0% to 23.8%, whereas the contribution from the southwest trajectories increases from 15.1% to 76.1%.

Based upon trajectory analysis, the moisture contributions from six regions that are of relevance to the moisture contribution of the SC rainfall, i.e., the Indian Ocean, the Bay of Bengal, the SCS, the Pacific Ocean, eastern China, and Eurasia, were previously
examined quantitatively (Chen and Luo 2018). The SCS region contributes the most (about one third) in both periods. After the SCS summer monsoon onset, the moisture contribution from the Bay of Bengal and Indian Ocean substantially increases from 17.1 % to 43.2 %, whereas that from the Pacific Ocean decreases from 21.0 % to 5.0 %.

b. Key synoptic systems

The large-scale circulation pattern favoring the PSRS heavy rainfall production over SC (Huang et al. 1986; Ding 1992, 1994; Zhao et al. 2007; Yuan et al. 2012) consists of a combination of relevant synoptic systems at the upper, middle, and lower levels. At the upper level, the southern Asian high and the westerly jet stream provide a divergent circulation for SC. At 500 hPa, there is often an anomalously strong subtropical high over the SCS owing to a westward extension of the WPSH. Four synoptic patterns favoring the production of EXHR, differentiated based on the characteristics of mid- and lower-troposphere flows, are summarized in Section 2.3. The southwesterly monsoon winds (sometimes embedded with LLJs) along the northwest edge of the WPSH help (i) enhance warm advection and water vapor transport toward SC, (ii) increase the lower tropospheric convective instability, and (iii) shape the pattern of the anomalous ascent over SC. The location of the WPSH largely determines whether water vapor could be transported to SC or the SCS, or to the mid–lower reaches of the Yangtze River. Using a subseasonal WPSH index, Guan et al. (2019) showed that the zonal variability of the WPSH on subseasonal time scales in early summer is closely associated with the Silk-Road pattern (Enomoto et al. 2003) wave train in the upper troposphere (Lu et al. 2002; Hsu and Lin 2007) and the East Asia/Pacific wave train pattern in the middle troposphere (Huang and Li 1987; Nitta 1987).

At the lower levels, formation and intensification of the relevant low-level cyclones can result from the dynamic (Wu and Chen 1985; Kuo et al. 1986; Chang et al. 1998) and heating effects (Li et al. 2014; Wan et al. 2017) of the TP; moreover, the low-level cyclones are sometimes related to low-pressure systems originating from the West Siberia region (Yuan et al. 2012). The low-level cyclones over SC during pre–summer can be associated with meridional propagation of the high-frequency intraseasonal oscillation with a 5–20-day period over SC and the SCS (Zheng and Huang 2018). Such propagation of the high-frequency intraseasonal oscillation is jointly governed by the internal atmospheric dynamics, including the vertical wind shear effect and the vorticity advection effect, as well as the moisture advection and sea/land–air interaction. Both the cloud radiation effect and wind evaporation can play some role by influencing the sea/land–air interaction and therefore the stability of near-surface air.

Miao et al. (2019) recently found that the low-frequency persistent heavy rainfall (defined as the 8–24-day filtered precipitation larger than one standard deviation of the filtered time series and persisting for at least three days) over SC during the PSRS may
be related to two low-frequency wave trains in the mid–high latitudes, i.e., the wave train crossing the Eurasian continent and the wave train along the subtropical westerly jet. An analysis of wave activity flux indicates that the Rossby waves originate from western Europe and the northern Mediterranean. The wave energy disperses toward eastern China along these two low-frequency wave trains from north to south and from west to east and then sinks over SC, leading to enhancement of the low-level relative vorticity and ascending air motion over SC.

c. Roles of LLJs

The concept of double LLJs, i.e., a boundary-layer jet (BLJ) and synoptic-system-related LLJ (SLLJ) in the lower-and-middle troposphere, and their relation with concurrent rainbelts over inland and coastal SC during the PSRS was proposed by Du and Chen (2018) based on a heavy rainfall case study. Their results suggested that the inland frontal rainfall is closely related to a SLLJ with maximum wind speed at 850–700 hPa, especially for its meridional wind component. The 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 before convection initiation, convergence at 950 hPa near the coast is relatively weak at the exit of a weak BLJ, whereas divergence at 700 hPa related to the entrance of a SLLJ is distant from the coast. With the southward approach of the cold front and the development of the BLJ at night, enhanced low-level convergence and mid-level divergence near the coast combine to produce updrafts. In addition to the enhanced mesoscale lifting, the double LLJs provide favorable conditions for the superimposed small-scale disturbances that can serve as effective moistening mechanisms of the lower troposphere during convection initiation. A sensitivity experiment with coastal terrain removed suggests that double LLJs and their coupling do indeed exert key effects on convection initiation, whereas collision between the BLJ and the terrain may enhance coastal convergence and amplify convection initiation (Du and Chen 2019).

This finding, as summarized schematically in Fig. 8, was supported by statistical analyses of a large ensemble of rainfall events during the 1980–2017 PSRS (Li et al. 2020). The SLLJ confronts the northerly, cold, dry airflows, providing strong synoptic forcing over the inland regions. In contrast, the BLJ’s northern terminus is located a few hundred kilometers away from the northerly airflows, making the synoptic lifting over the coast shallower and less obvious (Li et al. 2020). These differences in the structure and strength of synoptic forcing may explain the lower predictability of the pre-summer heavy rainfall at the coast (as compared with the inland regions) of SC (Huang and Luo 2017). Nevertheless, the BLJ often simultaneously strengthens with the SLLJ (Li et al. 2020), suggesting a close association between the BLJ’s strength and synoptic system variation, particularly the eastward-moving low-pressure originating in southwest China and the westward extension of the WPSH (Zhao et al. 2003).
3.3 Mesoscale phenomena and processes

MCSs are the dominant rainfall producers over SC during the PSRS. Xu et al. (2009) and Luo et al. (2013) investigated the characteristics of precipitation features defined as a contiguous area with near-surface raining pixels identified from the TRMM 2A25 data (Iguchi et al. 2000). These features were categorized into MCS, sub-MCS, and non-convection based on the extent and existence of convective pixels within the area. Both studies found that MCSs contribute a majority (close to 90 \%) of the total rainfall amount, despite their small population (less than 10 \%). Clearly, synoptic systems exert important effects on the initiation, propagation, and organization of MCSs formed within these systems (Huang et al. 1986). The factors governing the formation and evolution of the warm-sector MCSs often lie in the complex underlying surface, e.g., land–sea contrast (Chen et al. 2016), topography (Wang et al. 2014), and urban cluster (Wu et al. 2019), and the tropical-originated LLJ embedded in the monsoonal flow (Du and Rotunno 2018; Du and Chen 2019). Complicated smaller scale atmospheric processes, e.g., boundary colliding, mesoscale outflow boundaries (MOBs), gravity waves, and diurnal cycles, also play an important role (Wu and Luo 2016; Liu et al. 2018; Du and Chen 2019; Du and Zhang 2019), as found in other regions of the world (Kingsmill 1995; Piani et al. 2000; Ruppert et al. 2013). A conceptual model of an extreme-rain-producing MCS at the SC coast can be established for the early development and mature stages of the MCS (Fig. 9; Wang et al. 2014). The influencing factors and convective organization shown in this conceptual model are also found in many other extreme rainfall events near the SC coastline (e.g., Wu and Luo 2016; Liu et al. 2018).

Analyses of several extremely heavy rainfall events during the intensive observation periods of the SCMREX suggest a close relationship between the MOBs generated by previously-dissipated or active MCSs and the subsequent continuous convective initiation (Wang et al. 2014; Wu and Luo 2016; Liu et al. 2018). Despite their shallowness (e.g., approximately 0.5- to 1-km depth), the MOBs in coastal SC during the PSRS may continuously lift moist, conditionally unstable southerly oceanic air with little convective inhibition, leading to the formation and maintenance of extreme-rain-producing MCSs. Unlike at higher latitudes, the MOBs over SC present weak surface outflows that show little movement; these are crucial to the generation of extreme rainfall events lasting from tens of hours to several days.

At their mature stage, the extreme rainfall-producing MCSs at the SC coast during the PSRS often exhibit two concurrent modes of convective training, i.e., the training of meso-β-scale rainbands (with reflectivity > 35 dBZ) to the north of an MOB and the training of convective cells along individual rainbands (Wang et al. 2014; Wu and Luo 2016; Liu et al. 2018). The rainband training is formed under the combined influences of southerly or southwesterly environmental flows in the planetary boundary layer and the lower- and middle-troposphere, and the continuous convective initiation along the MOB. This rainband training organization bears some similarities with an extreme rain-producing MCS over central East China during the Meiyu season (Luo et al. 2014; Luo and Chen 2015). Moreover, Liu et al. (2018) noticed a rapid splitting and re-establishment process of a bow-shaped mesoscale rainband in an extreme rain-producing MCS along the SC coastline, which leads to the formation of two rainbands from one bow-shaped rainband within approximately 25 min. This process
occurs under three concurrent conditions: ample supply of warm and moist air from the ocean, a quasi-stationary MOB, and a bowing rainband with strong system-relative rear inflows intersecting with the MOB at the rainband’s southwest edge. Repetition of such a process contributes to the rainband training scenario.

3.4 Microphysical features

Active warm rain processes could play an important role in producing extreme rainfall over SC during the PSRS, as noted by Luo et al. (2020) for the Guangzhou dual-polarization radar observations of a record-breaking rain-producing storm that influenced the city of Guangzhou on May 7, 2017 (Huang et al. 2019). While radar reflectivity at horizontal polarization ($Z_{hh}$) is sensitive to hydrometeor size, the differential reflectivity ($Z_{DR}$) is affected by hydrometeor shape, orientation, and phase, and the specific differential propagation phase ($K_{DP}$) reflects amount of rainwater content (Bringi and Chandrasekar 2001). The microphysical features of the storm can be inferred using the occurrence frequency with altitude diagrams of $Z_{hh}$, $Z_{DR}$, and $K_{DP}$. Similar features are found in the diagrams using two thresholds of the 6-min rainfall (69 mm h$^{-1}$ and 153 mm h$^{-1}$) to sample the radar observations (Fig. 10). Below the 0-°C isotherm, the distribution of $Z_{hh}$ peaks approximately between 45 and 55 dBZ, the $Z_{DR}$ values are mostly within 0.5–2.5 dB, and $K_{DP}$ has high values up to about 5 deg km$^{-1}$. These results collectively suggest a large population of moderate-size spherical raindrops and a small quantity of large oblate raindrops. Of note is the significant skewing toward larger values with decreasing altitude below the 0-°C isotherm in the distributions, which indicates active warm-rain processes that lead to the growth of raindrop size and increase of rainwater amount as the raindrops fall. Also of importance is the absence of the ‘$Z_{DR}$ column’ (Conway and Zrnic 1993; Kumjian and Ryzhkov 2008), a polarimetric signature frequently detected within or on the periphery of the updraft maximum where supercooled drops and wet ice particles are lofted above the freezing level (Kumjian 2013). This suggests that the updraft in the storm might not be strong enough to lift a large population of liquid drops above the freezing level to support the riming processes.

The general contribution made by the mixed-phase (especially riming) and ice-phase microphysical processes to PSRS rainfall over SC remains unclear. The lightning flash rates produced by a storm (and vertical profile of radar reflectivity particularly in the −20°C to 0°C range) are indicative of the activeness of the riming processes (e.g., Zipser and Lutz 1994) as collision between high-density graupel and low-density ice crystals is a key mechanism in the charge separation needed for lightning formation (e.g., Takahashi 1978; Saunders 1993). The formation of a large amount of high-density graupel and hail requires an active riming processes in the mixed-phase range of the storm, which requires intense updrafts to lift abundant supercooled cloud/rain drops above the melting layer. The existence of graupel and small-size hail in the convective cores of a squall line passing over Guangdong in May is evident based on dual-polarization radar observations (Wu et al. 2018). The strongest (top 10 %) MCS-type precipitation features seen by TRMM during the post-monsoon-onset period of 1998–2010 have maximum radar reflectivity of about 40–45 dBZ at approximately the −20°C level, suggesting the likely presence of graupel (Luo et al. 2013; see Fig. 5a therein). However, the 2008–2013 statistics of cloud-to-ground lightning and rainfall over SC during the PSRS generally show highest flash densities over the inland region of the urban cluster in the Pearl River Delta (Xia et al. 2015), which is not collocated with the high-value centers of PSRS rainfall amount over Guangdong Province (Fig. 1). In particular, the accumulative rainfall centers near the coastline correspond to low flash densities. In addition, the afternoon peak of rainfall over SC accords with the appearance of an afternoon lightning peak, whereas lightning activity during the second rainfall peak from late night to early morning is very weak. This is consistent with the increased stratiform rainfall over SC during late night to early morning.

Based on the raindrop size distribution measurements made by the PARSIVEL disdrometers and the 2DVideo disdrometer during SCMREX, the mass-weighted mean diameter $D_a$ (mm) and the generalized intercept parameter $N_a$ (mm$^{-1}$ m$^{-3}$) can be estimated following Brandes et al. (2002). As shown in Luo et al. (2020; see Fig. 2 therein), the average values of $D_a$ and $N_a$ during SCMREX are higher and slightly lower, respectively, than those observed over inland East China (Chen et al. 2013; Wen et al. 2016) but quite close to those observed over Taiwan (Chen 2009) and Japan (Bringi et al. 2006). The similarity in the raindrop size distributions across SC, Taiwan island, and Japan (i.e., slightly larger mean size and lower population than those over inland East China) is perhaps related to lower aerosol pollution (Zhou et al. 2016) and the presence of sea salt aerosols (Zhang et al. 2012) over these coastal and island regions.
4. NWP studies

It has been demonstrated that numerical simulations of MCSs for mainland China during the warm season can be quite sensitive to initial atmospheric conditions (Wu et al. 2013) and the model physical parameterization schemes adopted (Luo et al. 2010; Luo and Chen 2015). While a single simulation or prediction cannot provide information on uncertainty, ensemble prediction serves to provide the statistical state of a
collection of possible results (Toth and Kalnay 1993; Tracton and Kalnay 1993), which can help improve the forecast quality and extend valid prediction periods (Schwartz et al. 2010; Clark et al. 2012). This section summarizes recent NWP studies focusing on predicting PSRS rainfall over SC. Only a limited number of such studies can be found in the literature, and they are mostly related to the SCMREX research activities.

4.1 Impact of data assimilation

The simulation of PSRS storms over SC is sensitive to initial moisture amount over the northern SCS (Lu et al. 2018). Assimilating observations from wind profiling radars (Zhang et al. 2016) and weather radars (Bao et al. 2017) in SC can improve quantitative precipitation forecast (QPF) skill, by reducing the initial errors in the dynamic and thermodynamic fields and consequently the storms’ evolution in the simulations.

The impact of assimilating horizontal wind data from 14 wind profiling radars (WPRs) in Guangdong was assessed by Zhang et al. (2016), using the operational partial-cycle data assimilation system based on a three-dimensional variational method at the Southern China Regional Meteorological Center. The analyses from the data assimilation system were used as initial conditions for the Global/Regional Assimilation and Prediction System model (Chen et al. 2008) (with a grid spacing of 3 km in the horizontal). The impact of assimilating WPR data on the QPF for May 2014 is evaluated by comparing the results of a control experiment with assimilation of the WPR data and a denial experiment without WPR data. The positive impact of WPR data assimilation on the forecast of atmospheric variables in the vertical and diagnostic fields at the surface is significant, especially those of surface wind fields in the 0–6-h range. The inclusion of WPR data also improves the QPF skill for light (> 0.1 mm h\(^{-1}\)) and heavy (> 20 mm h\(^{-1}\)) rainfall throughout the 12-h forecast period (Fig. 11) by alleviating the spin-up problem and reducing the predicted spurious precipitation (thereby alleviating over-estimations and false alarms), with the largest improvement in 6-h forecasts of heavy rainfall.

The effectiveness of assimilating Doppler-radar radial-velocity observations from an operational weather radar in coastal SC with an ensemble Kalman filter (Zhang et al. 2009) was demonstrated in a PSRS heavy-rainfall case study by Bao et al. (2017). Data assimilation in both deterministic and probabilistic experiments generally improves the prediction of a heavy-rain-producing MCS over land and an MCS over the northern SCS. Compared with the experiments using the longer data-assimilation time intervals, assimilating the radial-velocity observations at 6-min intervals tends to produce better forecasts. The experiment with the longest data-assimilation time span (2 h) and shortest time interval shows the best performance. The improved representation of the initial state leads to dynamic and thermodynamic conditions that are more conducive to earlier initiation of the inland MCS and a longer maintenance of the offshore MCS. However, a shorter data-assimilation time interval (e.g., 12-min vs. 30-min) or a longer data-assimilation time span does not always help in this case.

4.2 Evaluation and improvement of microphysics parameterization

Furtado et al. (2018) used a heavy rainfall case in May 2016 to identify a set of major drivers of model errors in the properties of deep convective clouds and rainfall; they also assessed how these errors are affected by the level of complexity inherent in the cloud microphysics and macrophysics schemes. The model is a high-resolution regional model configuration of the UK Met Office Unified Model, nested inside a coarser-resolution global simulation performed with the Met Office Global Atmosphere 6.1 configuration (Walters et al. 2017). It is shown that a small subset of the parameterization changes can reproduce most of the dependence of model performance on physics configuration. Particularly, biases that are due to the low-level clouds and rain are strongly influenced by cloud fraction diagnosis and raindrop size distribution, whereas variations in the effects of high clouds are strongly influenced by differences in the parameterization of ice crystal sedimentation. Therefore, these parameterizations give more insight into the causes of variability in model performance than does the number of prognostic variables in the microphysics scheme.

Using the same heavy rainfall case, Furtado et al. (2019) further investigated the effects of cloud-aerosol-interaction complexity on simulations of deep convection over SC. They found that different cloud droplet numbers in different parts of the domain can be better represented by including the processing of aerosol material inside cloud hydrometeors in the UK Met Office Unified Model simulations. Capturing these dependencies can be important for simulating organized convection and affects both the hydrological and radiative impacts of such systems in a manner consistent with, but not fully replicable by, one-way coupled
Four bulk microphysical parameterizations were compared in simulations of a squall line passing over SC during the SCMREX 2014 field campaign (Qian et al. 2018) using the WRF model with a 3-km grid spacing. The simulated ice-phase particles differ significantly among the microphysical parameterizations (Figs. 12d–h). However, rain evaporation dominates the cold pool generation and maintenance of the squall line in this case. Stronger rain evaporation generally contributes to stronger cold pools and thus faster movement and longer simulated squall lines (Fig. 12). The Stony Brook University–YLin (SBU–YLIN) scheme (Lin and Colle 2011) failed to capture the squall line (Fig. 12b), partially due to the turnoff of rain evaporation once environmental relative humidity is larger than 90%. Modifications to the rain evaporation calculation and saturation adjustment
Fig. 12. The 500-m AGL radar reflectivity from the Guangzhou radar (black dot) at 06:00 UTC (= LST − 8h) on May 22, 2014. Radar reflectivities and winds at 500 m AGL at 06:00 UTC on May 22, 2014 from the simulation using the SBU–YLIN scheme (b), the improved SBU–YLIN scheme (c), the Morrison graupel scheme (d), the Morrison hail scheme (e), the WSM6 scheme (f), the WDM6 graupel scheme (g), and the WDM6 hail scheme (h). The dashed brown line is the total precipitation during 04:00–08:00 UTC, May 22, 2014. The black solid line is the hourly temperature change from 05:00 to 06:00 UTC, May 22, 2014. The black dotted line represents the hourly precipitation during 05:00–06:00 UTC, May 22, 2014. The thick pink dashed line depicts the location of the squall line subjectively determined at 04:00, 05:00, 06:00, 07:00, and 08:00 UTC, May 22, 2014. (from Qian et al. 2018 with slight modification; ©American Geophysical Union. Used with permission)
method in the SBU–YLIN scheme significantly improve simulations of this squall line (Fig. 12c).

4.3 Ensemble forecast

Huang and Luo (2017) evaluated five global ensemble prediction systems in terms of their ability to predict PSRS precipitation over SC, including the European Centre for Medium-Range Weather Forecasts (ECMWF), U.S. National Centers for Environmental Prediction, Japan Meteorological Agency (JMA), Korean Meteorological Administration, and China Meteorological Administration (CMA). Evaluations of 5-day forecasts in three seasons (2013–2015) demonstrate the greater capability of probability matching forecasts, as compared with simple ensemble mean forecasts, and shows that the deterministic forecast comes a close second. These ensemble prediction systems overestimate light-to-heavy rainfall (0.1 to 30 mm (12 h)^{-1}) and underestimate heavier rainfall (> 30 mm (12 h)^{-1}), with JMA being the worst. By analyzing the synoptic situations predicted by the more capable (ECMWF) and less capable (JMA and CMA) ensemble prediction systems and the ensemble sensitivity for four representative cases of torrential rainfall, the transport of warm, moist air into SC by the low-level southwesterly flow (upstream of the torrential rainfall regions) is found to be a key synoptic factor that controls the QPF. The results also suggest that prediction of locally-produced, warm-sector torrential rainfall is more challenging than prediction of more extensively distributed, frontal torrential rainfall. A slight improvement in the performance is obtained by shortening the forecast lead time from 30–36 h to 18–24 h to 6–12 h for the two cases with strong large-scale forcing, but this improvement is not seen for the two locally-produced cases. The significant impact of low-level southwesterly flow (LLJ) on pre-summer rainfall forecast was confirmed in a single-case study based on the ECWMF global ensemble forecast (Zhang and Meng 2018).

An experimental convection-permitting ensemble prediction system based on the Global/Regional Assimilation and Prediction System (Chen et al. 2008) has been developed for QPF over southern China (Zhang 2018). This system produces 12-h forecasts at 0.03° horizontal resolution based on 16 perturbed members. Perturbations from downscaling, the ensemble of data assimilation, the time-lagged scheme, and topography are combined to generate the initial perturbations. SST is perturbed and a combination of downscaling and balanced random perturbations is used to perturb the lateral boundary conditions. Stochastically-perturbed parametrization tendencies, multi-physics, and perturbed parameters are all implemented. Compared with the control forecast for a 15-day period in May 2014, some deterministic guidance, including the forecast distribution with 90th percentile, probability-matched mean, and a linear combination of both, shows advantages in forecasting moderate and heavy rainfall. In addition, the optimal-member technique is superior in reducing bias. Probabilistic guidance demonstrates value over the control forecast in detecting potential threats of severe weather and lessening excessive warning, with both the optimal-probability and neighborhood-probability techniques leading to improvements in predicting lighter rainfall.

Zhang (2019) examined the multiscale characteristics of the different-source perturbations and their interactions in these ensemble forecasts. The meso-β-scale model-physics perturbations show faster growth and saturation, as well as larger magnitude than the meso-α-scale perturbations, especially in the presence of moist convection. For initial condition perturbations, damping is present for nonprecipitation variables, whereas rapid growth and saturation occurs for precipitation. Adding lateral boundary condition perturbations to initial-condition or model-physics perturbations causes linear impacts, which causes consistent (although small) perturbation increments. The nonlinear impacts of adding model-physics perturbations to initial condition perturbations have the most significant effects on meso-β-scale precipitation perturbations and can effectively improve precipitation prediction.

5. Concluding remarks

This review provides an overview of the recent progress in research on the pre-summer (April to mid-June) rainfall over South China (SC), including the temporal and spatial characteristics of the rainfall, new insights into the relevant multiscale processes, and modeling studies aimed at improving quantitative precipitation forecast (QPF) skill. The following areas and scientific questions are suggested for future studies.

- Cloud-precipitation microphysical processes and their representation in numerical weather prediction (NWP) models.

For pre-summer heavy rainfall in the warm-sector and that closely associated with synoptic systems, the characteristics and importance of warm-rain, mixed-phase, and ice-phase cloud microphysical processes deserve further investigation. Such studies should be conducted using newly-available, integrated cloud-
precipitation–lightning observations from dense surface weather stations, distrometers, dual-polarization radars, lighting location system, and new-generation geostationary satellites such as Himawari and Fengyun-4. These integrated observational datasets should be used to systematically evaluate and improve cloud microphysics parameterizations.

- Aerosol–convection–precipitation interactions.

What are the major types of natural and anthropogenic aerosols over SC? The latter type is increasingly important as SC becomes highly urbanized. How are the aerosols distributed and how do they vary temporally and spatially? How do the different types of aerosols influence convection initiation/evolution and fine-scale distribution of precipitation through changing the radiative transfer processes and thus atmospheric stability? Can the variation in aerosols significantly impact the rainfall intensity and distribution by acting as cloud condensation nuclei and ice-forming nuclei and subsequently changing the cloud-precipitation microphysical processes? To build a database for such studies, instrumented aircraft that can measure aerosol and cloud properties should be utilized in future field campaigns over SC.

- Past and future changes in the pre-summer rainfall over SC, and their causes.

How did rainfall of different intensities (especially extreme rainfall) over SC vary in the past and how will it change in the future? What are the separate and interactive roles played by global warming, large-scale circulation, and local effects of the urban cluster over coastal SC? A better understanding of these issues is important for engineering practice and urban infrastructure design (including the development of adaptive strategies) over densely populated and vulnerable areas of SC.

- Data assimilation for convection-permitting NWP.

Research should be conducted to (i) better understand the data assimilation impacts of various types of observations and (ii) more efficiently use newly available, high-resolution observations from dual-polarization radars and satellites. Of special importance is assessing the benefits offered by radars near the coastline and satellites, which can potentially provide valuable information about wind and clouds over the northern South China Sea (SCS).

- Ensemble generation methods for convection-permitting probabilistic QPF.

To better represent the unavoidable uncertainties in QPF, significant efforts need to be made in convection-permitting ensemble forecasting. This should include the development of perturbation methods, especially model-physics perturbations, that can well represent the features of convection evolution during the PSRS. Moreover, the nonlinear impacts of different-source perturbations should be examined and ensemble prediction system diagnostics in combination with radar and satellite nowcasts should be developed.

To conclude, this review highlights the complicated multiscale processes that lead to the pre-summer heavy rain over SC, many of which we have yet to understand. Many more studies are therefore necessary to improve our understanding, which will lead to better prediction of such heavy rain events. This outcome is of great importance to the millions of people living in the region as well as to the region’s economy.

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Appendix

List of acronyms

- BLJ: boundary layer jet
- CMA: China Meteorological Administration
- ECMWF: European Centre for Medium-Range Weather Forecasts
- EXHR: extreme hourly rainfall
- HUAMEX: Heavy Rainfall Experiment in South China
- JMA: Japan Meteorological Agency
- LLJ: low-level jets
- MCS: mesoscale convective system
- MOB: mesoscale outflow boundary
- NWP: numerical weather prediction
- PF: precipitation features
- PSRS: pre-summer rainy season
- QPF: quantitative precipitation forecast
- RSRE: rapid splitting and re-establishment
- SBU–YLIN: Stony Brook University–YLIn
- SC: South China
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