Nocturnal Convection Initiation over Inland South China during a Record-Breaking Heavy Rainfall Event

SIJIA ZHANG,a,b ZHAOMING LIANG,c DONGHAI WANG,a,b AND GUIXING CHEN,a,b
a Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China
b Key Laboratory of Tropical Atmosphere-Ocean System, Ministry of Education, Zhuhai, China
c State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China

ABSTRACT: A local long-lived convective system developed at midnight over inland South China, producing record-breaking rainfall in Guangzhou on 7 May 2017. This study examines the physical processes responsible for nocturnal convection initiation (CI) and growth. Observational analyses show that the CI occurs in the warm sector under weakly forced synoptic conditions at 500 hPa, while moderate but nocturnally enhanced low-level southeasterlies with a mesoscale moist tongue at 925 hPa intrude inland from the northern South China Sea. Convection-permitting model results show that mesoscale low-level convergence and increased moisture at the leading edge of the southeasterlies are favorable for CI dynamically and thermodynamically. Local ascent and potential instability are further enhanced by orographic lifting and warm moist air from the urban surface, respectively, which trigger convection in northern Guangzhou. The mesoscale moist tongue of southeasterly flows then meets convectively generated outflows, thereby maintaining strong updrafts and continuously triggering back-building convective cells in eastern Guangzhou. Sensitivity tests are conducted to estimate the relative roles of ambient southeasterly moist tongue and urban thermal effects. The southeasterly moist tongue provides moisture that is crucial for CI, while warm moist air from the urban surface is lifted at the leading edge of the southeasterlies and locally facilitates convection. Therefore, the mesoscale processes of lifting and moistening due to nocturnal southeasterlies and their strong interaction with the local factors (orographic lifting, urban heating, and cold-pool-related ascent) provide the sustained lifting and instability crucial for triggering the local long-lived convective systems. The multi-scale processes shed light on the understanding of the nocturnal warm-sector heavy rainfall inland.

KEYWORDS: Convection; Mesoscale systems; Rainfall; Local effects

1. Introduction

Convection initiation (CI) is the initial occurrence of a deep moist convective cell. The CI often leads to the development of MCSs that may produce heavy rainfall, particularly in the U.S. Great Plains (e.g., Carbone and Tuttle 2008; Weckwerth and Rotachmke 2019; Schumacher and Rasmussen 2020) and Asian summer monsoon regions (e.g., Luo et al. 2014; P. Li et al. 2020). Compared to daytime CI, nocturnal CI is more difficult to predict, as more complex processes at night are involved and observations are relatively insufficient (Wilson et al. 2018). Nocturnal CI events can produce hail, high winds, flooding, and even tornadoes based on radar climatology (Reif and Bluestein 2017). Given the high impact of nocturnal CI, some field campaigns have been conducted to gain insight into nocturnal CI and its near environment (e.g., Weckwerth and Parsons 2006; Wilson and Roberts 2006; Browning et al. 2007; Geerts et al. 2017). The LLJ has long been considered to play a role in triggering CI and heavy rainfall at night (e.g., Trier and Parsons 1993; Song et al. 2005; Trier et al. 2017; Gebauer et al. 2018; Du and Chen 2019; Trier et al. 2020). Weckwerth et al. (2019) summarized major nocturnal CI types and their key environmental features and their underlying physical processes based on results from the Plains Elevated Convection At Night (PECAN; Geerts et al. 2017) field campaign in the U.S. Great Plains. However, understanding and forecasting the location and timing of the nocturnal CI are still challenging issues for many regions around the world.

South China is a “natural convection laboratory” where the occurrences of deep convection are the highest in China with complex terrains and coasts (Luo et al. 2017; Zhang et al. 2017). CI hotspots are mainly observed on tropical islands and windward mountains, with nocturnal maxima at coastlines and offshore areas adjacent to coastal mountains (Bai et al. 2020). Previous studies mostly focus on the CI leading to the nocturnal heavy rainfall at the coasts of South China (e.g., Chen et al. 2014; He et al. 2016; Luo 2017). One important factor is southwesterly monsoon flows, sometimes in the form of marine boundary layer jets over South China (Du and Chen 2018; Du et al. 2020a). Coastal heavy rainfall events are often triggered by the interactions between monsoon southwesterlies and some mesoscale/local factors, which include land–sea breezes (Chen et al. 2016; X. Chen et al. 2017; N. Wu et al. 2020a), local orographic lifting and thermal

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Corresponding authors: Guixing Chen, chenguixing@mail.sysu.edu.cn; Donghai Wang, wangkan@mail.sysu.edu.cn

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effects (X. Chen et al. 2017; Chen and Zhang 2021), and precipitation-induced cold outflows (Wang et al. 2014; Wu and Luo 2016; Liu et al. 2018). Some studies note the CI occurrence in inland regions of South China, but the triggering mechanisms are less understood than those of coastal events (Liu et al. 2019; Sun et al. 2019; N. Wu et al. 2020b). Luo et al. (2020) summarized four major types of environmental conditions associated with extreme hourly rainfall events over South China: surface front type, low-level vortex type, low-level shear line type, and weak gradient type with southwest monsoons associated with extreme hourly rainfall events over South China (Huang 1986; Ding 1994; Luo et al. 2013, 2017; Luo 2017). Given the weak synoptic forcing at 500 hPa, the CI associated with warm-sector heavy rainfall relies more on the lower-tropospheric conditions and/or local forcings over complex underlying surfaces. The CI of warm-sector heavy rainfall remains a key issue for operational forecasting. Therefore, placing the findings of nocturnal CI over inland South China into a broader context of scientific understanding provides a benefit for advancing our knowledge of heavy rainfall.

In this study, we investigate nocturnal CI mechanisms in inland warm-sector areas over South China and explore key factors during a high-impact event. Convective systems developed locally at midnight of 6 May 2017 in the inland areas of Guangzhou, South China. They lasted for ~10 h with two convective stages, producing a highly localized but record-breaking rainfall event and inducing severe floods in the early morning of 7 May (Fu et al. 2018; Tian et al. 2018). This nocturnal event initiated in the warm sector over South China under a weakly forced environment at 500 and 850 hPa, although the typical synoptic conditions of warm-sector heavy rainfall, such as monsoon southeasterlies and low-level jets, are absent (Sun et al. 2019; Luo et al. 2020). Disturbed lower-tropospheric conditions featuring onshore low-level moderate southeasterly flows from the northern South China Sea (SCS) are thought to play a role (Wu et al. 2018; Xu et al. 2018; Zeng et al. 2018). Huang et al. (2019a,b) suggested that synoptic-scale southerly winds provided a crucial moisture source for producing extreme rainfall. Yin et al. (2020) found that the local heating of urban Guangzhou was important for the first-stage heavy rainfall. Wu et al. (2021) argued that the local orographic blocking and nighttime cooling of the Huadu hills in northern Guangzhou was key for the first-stage CI. Gao et al. (2021) noted that land surface processes may also have an impact on convective systems. In the second stage, a convectively induced cold pool and a meso-γ-scale vortex were found to sustain intense updrafts for the long-lived convective system (M. Li et al. 2020; Yin et al. 2020). Previous studies have highlighted a variety of factors in this event but have not interpreted why long-lived convective systems are locally induced at night and sustained with weak-to-moderate southeasterlies.

In this study, we examined the atmospheric conditions of convective systems with an emphasis on the phenomena related to onshore southeasterly flows based on observational data. Then, we estimated the detailed roles of the ambient southeasterlies and mesoscale/local effects in convection triggering and growth based on a series of real numerical experiments. Our main goal was to clarify the physical processes responsible for the nocturnal CI inland that lead to warm-sector heavy rainfall over South China. The rest of the paper is organized as follows. Section 2 introduces the data used in this study and the settings of the numerical model. Section 3 gives observational analyses of the CI processes and associated synoptic-to-mesoscale atmospheric conditions. Based on the model results, the analyses of CI processes in terms of mesoscale/local dynamic lifting and potential instability are shown in section 4. The relative contributions of the key atmospheric factors in CI processes are further discussed in section 5 based on sensitivity tests. Our conclusions are drawn in section 6.

2. Data and methods

a. Data

In this study, we focused on a local heavy rainfall event on 7 May 2017. To show the observed rainfall systems, we used hourly data from a dense network of rain gauges. The satellite data of the NOAA Climate Prediction Center morphing technique (CMORPH) were also used to show rainfall over a large domain. The CMORPH data provide the rain rate at a 30-min interval with an 8-km grid spacing (Joyce et al. 2004). The hourly ERA5 from the ECMWF (Hersbach et al. 2020) was used to show synoptic-scale features. To show convective-scale features, we used radar observations at 6-min intervals, quality-checked wind profiler data, and hourly surface observations from densely automatic weather stations (e.g., winds at 10 m AGL). The assimilated data from the NCEP FNL Operational Model Global Tropospheric Analysis provided the initial and boundary conditions. The topography data were chosen from the Shuttle Radar Topography Mission (SRTM) at 3-arc-s resolution.

b. Setup of numerical experiments

Convection-permitting numerical model results were obtained using the Advanced Weather Research and Forecasting (WRF) Model (Skamarock and Klemp 2008) v3.9.1 in this study. The model was initialized at 2000 LST (LST = UTC + 8 h) 6 May and nudged by observations. The observation nudging is described later in this section. The spinup time of ~4 h ahead CI was found to be optimal in this event. In practice, a short spinup time has been used in many previous studies for CI simulations over South China (e.g., Du and Chen 2019; Huang et al. 2019a; Yin et al. 2020; Huang et al. 2020). We used the LST to describe time hereafter. Figure 1a shows the three nested domains used in the numerical simulation at 9-, 3-, and 1-km horizontal grid spacings. The simulated data in the 1-km mesh domain were output every 10 min. The Kain–Fritsch cumulus parameterization (Kain 2004) was used for the 9-km domain, and no cumulus parameterization was used for the inner two domains. Other physical parameterization schemes were the same for all three domains, including the WRF double-moment 6-class (WDM6) microphysics scheme (Lim and Hong 2010), the revised Rapid Radiative Transfer Model (RRTM) GCM parameterization scheme (Mlawer et al. 1997), and the Rapid Radiative Transport Model (RRTM) GCM parameterization scheme (Mlawer et al. 1997).
Transfer Model (RRTMG) longwave and shortwave radiation scheme (Iacono et al. 2008), the Unified Noah Land Surface Model (Ek et al. 2003; Tewari et al. 2004), and the Yonsei University Scheme (YSU) planetary boundary layer parameterization (Hong et al. 2006), which has been widely used for simulating warm-sector heavy rainfall over South China (e.g., Zhang and Meng 2019; Du et al. 2020a; Yin et al. 2020). A single-layer urban canopy parameterization with default parameters was activated using the Noah land surface model coupled with the Single Layer Urban Canopy Model (SLUCM; Kusaka et al. 2001). The initial and lateral boundary conditions were provided by the NCEP FNL dataset with a spatial resolution of 1° × 1° at 6-h intervals. The topography data for the inner two domains were at 3-arc-s resolution (approximately 90 m), which resolve the local orography in northern Guangzhou. A total of 74 sigma levels were used in all three domains with fine vertical resolutions (stretching from 20 to 100 m) in the lowest 1 km, which helped to simulate boundary layer atmospheric processes.

To better capture local convective disturbances and CI processes, observation nudging via a four-dimensional data assimilation (FDDA) function was applied to the innermost domain during the whole period of modeling (Stauffer and Seaman 1990, 1994; Liu et al. 2005, 2006). Specifically, we nudged the soundings at 2000 LST (1200 UTC) 6 May and aircraft reports at approximately 2300 LST (1500 UTC) upstream of Guangzhou and near the location of CI, which may improve the representation of low-level atmospheric conditions in the model. We also nudged the near-surface data at 3-h intervals over a local region around Guangzhou. The observation data were nudged mainly during the first 3 h, while few data were nudged afterward. We may consider that the model results were assimilation in the first 3 h and some simulations afterward. The observation-nudging procedure with different coefficients and data sources also allowed us to test the sensitivity of CI to different atmospheric factors, which is presented in section 5. We tested the possible inconsistency in observation data by either nudging the wind fields or the moisture and temperature fields and found that this issue does not influence our analysis (figure not shown). The key coefficients in the nudging algorithms we used (e.g., nudging strength and nudging maximum distance) have been tuned so that the convective systems of the model results resemble well the observed ones.

3. Synoptic-to-mesoscale analyses of convection initiation and associated atmospheric conditions

a. Spatiotemporal evolution of the convective systems

A rainfall event initiated in Guangzhou city over South China and produced record-breaking rainfall. This event initiated in an environment characterized by weak synoptic-scale disturbances over Southeast Asia (Fig. 1a). The 12-h rainfall amount exceeding 100 mm in this event was confined to a 50-km area of Guangzhou city approximately 120 km from the coastlines of the SCS (Fig. 1b). The horizontal grid spacing of domains D1, D2, and D3 is 9, 3, and 1 km, respectively. Spatial distributions of automatic weather stations, radar, and wind profiles are shown in (b) by colorful dots, brown stars, and brown asterisks, respectively. The soundings that were initially nudged into the model at 2000 LST 6 May are shown by the red asterisk. The aircraft reports that were nudged into the simulation from 2239 to 2301 LST 6 May are shown by the red plus. The solid black lines and gray fill in (b) represent city borders and the elevation (contours: 100, 200, 300, and 400 m), respectively.

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To show the evolution of the convective system, we examined the observed radar reflectivity in Guangzhou in Fig. 2. At 0000 LST 7 May 2017, the first radar echo (defined with a radar reflectivity factor exceeding 35 dBZ), marked with A, initiated immediately south of the Huadu hills (Fig. 2a). Convective system A developed rapidly near the hills (Fig. 2b). From 0100 to 0200 LST, convective system A remained the strongest, while several other convective cells developed in the surrounding areas of the Huadu hills (Figs. 2c,d). By 0306 LST, convective system A reached its mature stage with a local area that was ~20 km wide (Figs. 2e). Additionally, another new convective system B emerged near the southeast of the full-fledged system A in eastern Guangzhou. In the following two hours, convective system B grew rapidly, while system A decayed (Figs. 2e,f). The local, intense, and quasi-stationary convective system A and the succeeding system B near the southeast lasted for ~5 h in Guangzhou, which can be the first convective stage and the focus of this study. After systems A and B, back-building convective system C occurred in the coastal area of South China (Fig. 3). In particular, high specific humidity exceeding 15 g kg\(^{-1}\) near-surface southerly winds were relatively weak (~2 m s\(^{-1}\)) at 1700 and 2000 LST 6 May 2017 in targeted domain 3 (Figs. 3c,d), and they strengthened to 4–6 m s\(^{-1}\) from 2300 LST 6 May to 0200 LST 7 May 2017 (Figs. 3e,f). This nighttime enhancement of the low-level winds was closely related to the confluence of two marine moist flows from the northern SCS and the Taiwan Strait. The marine flow from the Taiwan Strait (marked as the arrows in blue) was induced by the anticyclonic system at ~120ºE that moved from Central China to the East China Sea. The enhancement of the southeasterlies at night was mainly attributed to the ageostrophic winds in the northern SCS. The ageostrophic wind shifted from the northerly wind at 1600 LST, the northeasterly wind at 1900 LST, and the easterly wind at 2200 LST to the southeastern wind at 0100 LST (Fig. 4). Such a clockwise rotation of ageostrophic winds matched the theory of the boundary layer inertial oscillation caused by the imbalance between the pressure gradient force and Coriolis force (Blackadar 1957; Van de Wiel et al. 2010). This process has also been adopted by previous studies to explain the nocturnal enhancement of low-level southerly winds over the Great Plains LLJ and in eastern China (Huang et al. 2010; G. Chen et al. 2013, 2017; X. Chen et al. 2015; Fedorovich et al. 2017; Du et al. 2020a).

The specific humidity at 925 hPa was larger than 13 g kg\(^{-1}\) in the coastal area of South China (Fig. 3). In particular, high specific humidity exceeding 15 g kg\(^{-1}\) was established at 115ºE with a zonal extension of ~100 km just east of domain D3 at 1700 LST, indicating a moist tongue, as noted by the gray-dashed contour in Fig. 3e. This moist tongue was enhanced with an extension of ~330 km at 2000 LST, with the maximum specific humidity exceeding 16 g kg\(^{-1}\) (Fig. 3d). The enhancement of the moist tongue was closely related to the low-level convergence in the coastal area (approximately 113º–116ºE) because of the confluence of two marine flows from the South China Sea and the Taiwan Strait. The moist tongue then extended inland toward the center of domain D3 along with the enhanced southeasterlies near midnight (Figs. 3e–f). The enhancement and inland intrusion of the southeasterlies and the related moist tongue in domain D3 correspond well to the observed convective systems in terms of time and location. The synoptic-scale pattern seems to provide favorable mesoscale conditions for the growth of convective systems in local areas of Guangzhou, which is the focus of our following sections.

In this section, we analyze the synoptic-scale pattern and mesoscale conditions with an emphasis on low-level wind conditions. This event occurred under weakly forced synoptic conditions at 500 and 850 hPa (Figs. 3a,b). A weak high pressure pattern (or a mesoscale ridge) with southerly winds to its west flowing into the region of interest was seen at 500 and 850 hPa over the northern SCS. The easterly-to-southerly winds prevailed at 925 hPa over the northern SCS, while the easterly-to-southerly winds were relatively weak (~2 m s\(^{-1}\)) at 1700 and 2000 LST 6 May 2017 in targeted domain 3 (Figs. 3c,d), and they strengthened to 4–6 m s\(^{-1}\) from 2300 LST 6 May to 0200 LST 7 May 2017 (Figs. 3e,f). This nighttime enhancement of the low-level winds was closely related to the confluence of two marine moist flows from the northern SCS and the Taiwan Strait. The marine flow from the Taiwan Strait (marked as the arrows in blue) was induced by the anticyclonic system at ~120ºE that moved from Central China to the East China Sea. The enhancement of the southeasterlies at night was mainly attributed to the ageostrophic winds in the northern SCS. The ageostrophic wind shifted from the northerly wind at 1600 LST, the northeasterly wind at 1900 LST, and the easterly wind at 2200 LST to the southeastern wind at 0100 LST (Fig. 4). Such a clockwise rotation of ageostrophic winds matched the theory of the boundary layer inertial oscillation caused by the imbalance between the pressure gradient force and Coriolis force (Blackadar 1957; Van de Wiel et al. 2010). This process has also been adopted by previous studies to explain the nocturnal enhancement of low-level southerly winds over the Great Plains LLJ and in eastern China (Huang et al. 2010; G. Chen et al. 2013, 2017; X. Chen et al. 2015; Fedorovich et al. 2017; Du et al. 2020a).

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FIG. 2. Observed composite radar reflectivity (color fill, dBZ) over the Guangzhou region on 7 May 2017. The thick dotted circle in blue represents the major convective systems A and B. The solid black lines represent city borders. The thin black contours indicate the elevation (contours: 100, 200, 300, and 400 m).
FIG. 3. (a),(b) Geopotential height (color fill, gpm) at 500-hPa levels and wind vectors (black, m s$^{-1}$) at 850-hPa level at (a) 2000 and (b) 2300 LST 6 May 2017 from the ERA5. The blue administrative boundaries represent Guangdong Province. (c)–(f) Specific humidity (color fill, g kg$^{-1}$) and wind vectors (black, m s$^{-1}$) at 925-hPa level and mean sea level pressure (brown contours, hPa) at (c) 1700, (d) 2000, (e) 2300 LST 6 May and (f) 0200 LST 7 May 2017 from the ERA5. The dark green dot fill patterns represent the enhancement of southerly wind, which is larger than 1 m s$^{-1}$. The green box indicates domain 3 in Fig. 1a. The letter H in navy represents the position of the surface high. The bold, colored arrows denote the northeasterly outflows (dark green, light blue) and the marine easterly to southeasterly flows from the northern SCS (navy). The purple dashed line is the synoptic front. The white dashed lines represent the moist tongue (specific humidity of 15.5 g kg$^{-1}$).
was related to the relatively low temperature over the Huadu hills (Fig. S3), as also noted by Wu et al. (2021). The local katabatic northerlies due to nighttime orographic cooling may contribute to terrain-induced orographic circulations with intruding southeasterlies and therefore play a role in CI. At approximately CI (0000–0100 LST), strong updrafts (over 1.6 m s$^{-1}$) developed at 1–2 km AGL at the leading edge of the southeasterlies, as shown by the wind profile at Huadu (Fig. S2b). The intrusion of the enhanced southeasterly flows therefore seemed to intensify the low-level lifting south of the hills that was favorable for the CI of system A at night (Fig. 2a), which will be discussed in the next section.

From 0100 to 0400 LST, the northeasterly wind related to the downdrafts (Fig. S2b) occurred near the south of the Huadu hills with a low-temperature center (Figs. 5f–i, Fig. S3f), which indicated the formation of a convectively induced cold pool. The northerly outflows of the cold pool collided with the marine southeasterly flows, and the convergence boundary (dashed line) moved slowly southward to the eastern region of Guangzhou during 0200–0400 LST (Figs. 5g–i). Accordingly, convective system A was mature at ~0300 LST and dissipated thereafter (Figs. 2d–f), while convective system B was developing in eastern Guangzhou (Figs. 2d,e).

In summary, the observational analyses suggest that the quasi-stationary, local, and long-lived convective systems developed at the leading edge of the marine low-level southeasterlies in the warm sector under weakly forced synoptic conditions in the mid- to upper troposphere. The convective development, including the timing and location of CI prior to intense rainfall, was closely associated with an inland intrusion of moderate but strengthening low-level southeasterly flows with an arc-shaped mesoscale moist tongue. The moist onshore southeasterlies may play a role in the CI, which will be further illustrated via the convective-scale model results in the next section.

4. Processes of nocturnal CI revealed by convective-scale modeling

a. Verification of the simulated convective system and atmospheric conditions

To further examine the roles of onshore low-level marine southeasterlies in triggering CI, we obtained cloud-permitting model results using WRF as introduced in section 2b. The modeling convective system A initiated ~8 km south of the Huadu hills at 0020 LST 7 May 2017 (Fig. 6a). System A
developed rapidly near Huadu hills, while it merged with some smaller convective cells nearby (Fig. 6b). It became mature near the Huadu hills with an approximate 38-km width of the storm during 0220–0300 LST (Figs. 6c,d), producing a maximum rainfall rate of over 70 mm h\(^{-1}\) at 0200–0300 LST (figure not shown). The modeling convection was more widespread with stronger reflectivity than the radar observation. The model deficiency may be related to a start of cycling without hydrometer assimilation, which may influence the boundary layer and microphysics processes (Huang et al. 2020; Wu et al. 2021). As we focused on the convection near the Huadu hills, the numerical simulation reproduced key features of the observed

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**FIG. 5.** Observed hourly wind field at 10 m AGL (wind barbs, m s\(^{-1}\)) from 2000 LST 6 May to 0400 LST 7 May 2017. (a)–(e) The dotted black lines represent the leading edge of the southeasterlies where the southerly wind is almost zero, and (f)–(i) the thicker lines represent the convergence boundary between the northerly outflows and the southeasterlies. The thin and thick wind barbs indicate winds larger than 2 and 4 m s\(^{-1}\), respectively. The color of the wind barbs indicates the direction of the wind. The barbs in navy, light blue, yellow, and orange represent the southeasterly, southwesterly, northwesterly, and northeasterly winds, respectively. The brown triangles in (a) denote the locations of wind profilers. The green stars in (e) and (h) denote the CI locations of convective systems A and B, respectively.
system A in terms of the time/location of the CI and convective growth (cf. Figs. 2a–d and Figs. 6a–d). Following the development of system A, simulated convective system B emerged near the southeast of A (Figs. 6b,c) and grew rapidly in eastern Guangzhou (Figs. 6d–f). The modeled system B occurred earlier than the observed B (less than 2 h) with a displacement to the northeast of ∼35 km. The simulated radar echoes were stronger and more widespread than radar observations (cf. Figs. 6c–f and Figs. 2d–f), which led to rainfall over a larger area (figure not shown). Overall, the convection-permitting model results generally reproduced the long-lasting local convective systems in the Guangzhou region after midnight, which included the convective system A near the windward hills in good agreement with the observations and the succeeding system B with some bias in timing, location, and strength.

We then evaluated the key atmospheric conditions in the model results. Both the model and observation exhibited the nocturnal enhancement and inland movement of the southeasterly flows at 2100–2300 LST 6 May 2017 before CI (cf. Figs. 5b–d, Figs. 7a–c) and the quasi-stationary leading edge of the enhanced southeasterlies several to the south of the Huadu hills at 0000–0200 LST 7 May during the CI processes (Figs. 5e–g and Figs. 7d–f). The induced updrafts near midnight at the CI site were also seen in both sounding observation and model results (Fig. S2b and Fig. 8b). The ageostrophic wind fields of the model results exhibited a clockwise rotation at night from the easterly wind at 2200 LST to the southwesterly wind at 0300 LST (Fig. S4), which is consistent with the ERA5 (Fig. 4). Therefore, the WRF Model reproduced the feature of boundary layer inertial oscillation that led to the nocturnal enhancement of onshore low-level southerlies. Along with the enhanced southeasterlies, the modeled moist tongue with a specific humidity larger than 16 g kg⁻¹ extended from the southeastern coast to the inland urban areas, while the humidity was relatively low in the western coast and the northern mountainous area of domain D3 (Fig. 7). The modeled distribution of the moist tongue agreed with the spatial features seen in the ERA5 (Figs. S6a,b). The northern terminus of the moist tongue reached the southern Huadu hills (∼23.5°N) at the leading edge of the southeasterlies where system A occurred, which was consistent with the high humidity

Fig. 6. Simulated composite radar reflectivity (color fill, dBZ) over the Guangzhou region. The thick dotted blue circles represent the convective systems. The solid black lines represent city borders. The thin black contours indicate the elevation (contours: 100, 200, 300, and 400 m).
and the wind convergence seen near the CI location in the surface observations and sounding data (Figs. S6c,d). The cold pool associated with system A and its northerly cold outflows with low humidity were present in the modeled results after 0200 LST (Figs. 7f,g). The northerly outflows then moved southward at 6–12 m s\(^{-1}\) to eastern Guangzhou, where system B developed during 0300–0400 LST (Figs. 7g,h), which corresponded to those in the surface and sounding observations.
FIG. 8. Height–latitude cross sections of equivalent potential temperature \( \theta_e \) (filled color, K), southerly wind (green lines, 4 and 6 m s\(^{-1}\)), and wind field (vectors, vertical velocity multiplied by 5, m s\(^{-1}\)). The white dashed lines are the head of the moist tongue with \( \theta_e \) of 350 K. The left and right columns are along the left and right boxes shown in Fig. 7, respectively. The terrain is represented by a black line and a white filled color. The purple lines represent the range of Fig. 9.
of a cold pool with outflows. The model results reproduced the three key stages for the local convective systems: the period of 1–3 h before CI with the inland intrusion of the marine southeasterlies and moist tongue, the CI and convective growth of system A at the leading edge of the southeasterlies near terrains, and the transition from A to succeeding B related to the southward extension edge of the southeasterlies near terrains, and the transition land intrusion of the marine southeasterlies and moist tongue, AGL (Fig. 9b). The lower-tropospheric moist tongue enhanced the local humidity of the southern Huadu hills to 85% of system B were generally reproduced.

In summary, compared with the ERA5 and observations, the model results reproduced the three key stages for the local convective systems: the period of 1–3 h before CI with the inland intrusion of the marine southeasterlies and moist tongue, the CI and convective growth of system A at the leading edge of the southeasterlies near terrains, and the transition from A to succeeding B related to the southward extension edge of the southeasterlies near terrains, and the transition land intrusion of the marine southeasterlies and moist tongue, AGL (Fig. 9b). The lower-tropospheric moist tongue enhanced the local humidity of the southern Huadu hills to 85% of system B were generally reproduced.

b. Dynamic lifting and potential instability associated with CI

We examine the mesoscale/local physical processes governing the CI of convective system A and its transition to system B in this section. Note that system B initiated ~2 h after the CI of system A. The hourly sections of local atmospheric conditions were chosen to show the developing stages from the stage 1–3 h before CI to the convective growth and the mature/decaying stages.

During 1–3 h before the CI of system A, the marine weak-to-moderate southeasterlies strengthened by ~2 m s$^{-1}$, and their leading edge (dashed line) moved inland during 2100–2300 LST 6 May (Figs. 7a–c). The enhanced southeasterlies resulted in moderate convergence ($3 \times 10^{-4}$ s$^{-1}$) several kilometers to the south of the Huadu hills. The enhanced southeasterlies also resulted in the inland intrusion of marine moist air from the southeastern coasts. Then, the moist tongue (marine moist air with specific humidity larger than 16.6 g kg$^{-1}$) arrived at ~23.3$^\circ$N near the Huadu hills in northern Guangzhou at 2330 LST. The moist tongue passed through the urban areas of Guangzhou at 22.5–23.3$^\circ$N. The maximum high-$\theta_e$ air masses (above 352 K) at the lowest 200-m layer were established mainly in the urban areas (Fig. 8a; Fig. S3), which denoted the urban heating effect of Guangzhou city as in Yin et al. (2020). Accordingly, CAPE was estimated as ~1000 J kg$^{-1}$ at 800 m AGL and as ~1600 J kg$^{-1}$ at the lowest 200 m AGL (Fig. 9a).

An hour prior to the initiation of system A, the leading edge of enhanced southeasterlies remained quasi-stationary to the south of the Huadu hills (Fig. 7d). The southeasterlies were combined with the northerly orographically induced katabatic winds from the hills to strengthen the convergence around the hills ($12 \times 10^{-4}$ s$^{-1}$) from the surface to 700 m AGL (Fig. 9b). The lower-tropospheric moist tongue enhanced the local humidity of the southern Huadu hills to more than 17.8 g kg$^{-1}$ due to moisture advection of marine southeasterlies (Fig. 7d). The high-$\theta_e$ air (349 K) of the moist tongue was lifted to 1 km AGL at the leading edge of the southeasterlies (Fig. 8b). Additionally, the near-surface high-$\theta_e$ air masses in urban areas (their heads marked by white dashed lines) were stretched to 600 m AGL near the hills (Fig. 8b). Therefore, the warm moist air from the urban surface was also elevated to the lower troposphere by the enhanced upward motion (Figs. 8b and 9b). A high CAPE above 1000 J kg$^{-1}$ was seen from the surface to 1 km AGL, suggesting that a relatively deep layer of potential instability was established for CI (Fig. 9b). A narrow region of low CIN less than 4 J kg$^{-1}$ was also seen south of the hills, while the CIN was larger than 40 J kg$^{-1}$ outside of the moist tongue (Fig. S7). The confined pattern of low CIN was thus favorable for localized convection south of the hills. Under favorable lifting conditions, the lower-tropospheric moist tongue was thus combined with near-surface urban heating to produce potential instability in northern Guangzhou. Therefore, we observed that all these dynamic and thermodynamic processes interacted with each other locally and provided favorable lifting/instability conditions for CI.

An hour after system A was initiated, the column-integrated moisture was enhanced by the advection of the southeasterly moist tongue and the lifting at the leading edge of the southeasterlies, as the southeasterlies were blocked by the hills (Figs. 7d,e and 8d,e). The convergence was strong ($14 \times 10^{-4}$ s$^{-1}$) at the leading edge of the southeasterlies, and its associated rising motions larger than 2 m s$^{-1}$ penetrated into the free atmosphere above 2 km AGL (Fig. 9c). The rising motions lifted high-$\theta_e$ air masses (over 348 K) from both the lower-tropospheric moist tongue and the urban surface to fuel the rapidly growing convection (Fig. 8c). In summary, the nocturnally enhanced onshore southeasterlies under the boundary layer inertial oscillation seemed to induce mesoscale processes interacting with local factors, which made possible the formation of convective systems inland at night. In this case, the mesoscale convergence at the leading edge of enhanced southeasterlies at night was locally enhanced by the orographic effects (e.g., blocking and lifting) to establish low-level ascent for CI of system A. The inland intrusion of the southeasterlies also enabled the mesoscale moist tongue and local urban heating to be elevated together, producing potential instability for convective growth.

When system A matured, a cold pool formed near the Huadu hills. The cold pool was characterized by relatively dry air and northerly winds of ~6 m s$^{-1}$ (Figs. 7f,g) and negative thermal buoyancy (Du et al. 2020b) of ~0.04 m s$^{-2}$ from the surface to ~200 m AGL (Fig. 9d), and it was related to the evaporation-induced downdrafts bringing low-$\theta_e$ air to the surface (Fig. 8d). The northerly outflows of the cold pool in the lowest 400 m AGL collided with the southeasterlies, which acted to sustain the convection and its associated rising motion. As a result, the warm moist air from both the moist tongue and the urban surface was continuously fed into the convective system. Additionally, the downdrafts of the cold pool were approximately 20 km north of the convective updrafts. The displacement of downdrafts from updrafts was conducive to sustaining strong convection that produced a highly intense rain rate, as also pointed out by Huang et al. (2019b).

In the following hours, $\theta_e$ in warm moist air decreased, which became less supportive of convection (Fig. 8e). During
FIG. 9. Vertical cross sections of convergence (color fill, $s^{-1}$, multiplied by $10^4$), thermal buoyancy (blue contours, $\leq -0.04$ m s$^{-2}$ with an interval of 0.02 m s$^{-2}$), convective available potential energy (CAPE; purple contours, 1000 and 1600, J kg$^{-1}$), convective inhibition (CIN; brown contours, 2 J kg$^{-1}$), and wind field (vectors, vertical velocity multiplied by 5, m s$^{-1}$). The CAPE is calculated for the air particle as a source from each layer. The gray lines along the $x$ axis are used to calculate the average values in Fig. 10.
the same period, strong northerly outflows of the well-developed cold pool extended slowly southward to 23.2°N. Their collision with the southeasterlies continued to support convergence and its associated updrafts (Figs. 7g, h, and 9e), which alone seemed inadequate to sustain convective growth. Overall, the warm moist air being lifted and induced potential instability at the leading edge of the southeasterlies from the moist tongue and urban surface is shown to be crucial for the formation and growth of convective system A.

To further quantify the formation and development associated with system A, we examine the time series plot of the southerly wind, convergence, and cold pool at the CI site. The convergence south of the hills was gradually enhanced due to the inertial oscillation (Fig. S3). The induced dynamic lifting was thought to contribute to the formation of system A. After CI, the thermal buoyancy decreased dramatically and became negative at 0130 LST, suggesting the formation of a convectively induced cold pool. Then, the northerly outflows from system A arrived at site B prior to the initiation of system B (Fig. 9g). Therefore, the cold outflows of the developing cold pool were strong due to the convective feedback from system B and continued to collide with the southeasterly moist tongue (Fig. 9g). The upward motions were thought to ease the formation of low CIN to initiate system B. In the following hours, the outflows of the developing cold pool were strong due to the convective feedback from system B and continued to collide with the southeasterly moist tongue so that strong convergence and its associated rising motion were sustained in high-CAPE air for convective growth of system B (Figs. 7g–i, 8h–j, and 9h–j).

Based on the time series plot (Fig. 10b), the cold pool and its outflows from system A arrived at site B prior to the initiation of system B, as the thermal buoyancy was negative and the northerly wind was enhanced at 0200 LST. Convergence strengthened to $6 \times 10^{-4}$ s$^{-1}$ due to northerly cold outflows colliding with the southeasterlies prior to the initiation of system B (Fig. 9g). Therefore, the cold outflows from system A were essential for initiating system B by colliding with the southeasterly moist tongue, which was also noted by previous studies of the same case (e.g., Huang et al. 2019a; Yin et al. 2020; Wu et al. 2021). Similar processes are sustained in storm C, which was triggered by quasi-stationary cold outflows converging with the southeasterly moist tongue. These sustaining processes thus explain the formation of the long-lived convective systems (from A, B, to C) and associated localized heavy rainfall. The role of the cold pool in CI and convection organization has also been seen in other events over South China (e.g., Wang et al. 2014; Wu and Luo 2016; Du et al. 2020b). In this event, the cold pool is shown to interact strongly with a mesoscale moist tongue to sustain back-building convective cells, leading to long-lasting convective systems.

**Fig. 10.** Temporal evolution of the thermal buoyancy (blue lines, m s$^{-2}$), divergence (pink lines, $10^{4}$ s$^{-1}$), and $V$ component of wind (black lines, m s$^{-1}$) at 250 m AGL for (a) convective system A and (b) convective system B. Their values are averaged along the gray lines in Fig. 9.
In summary, the enhanced convergence and its associated rising motion at the leading edge of the southeasterlies allowed the mesoscale moist tongue to fuel system A. They also lifted the warm moist air from the urban surface to the level of free convection so that the urban effect could locally facilitate convective system A. The evolution of systems A and B exhibited some different features. The low-tropospheric moist southeasterly inflow to system A was relatively shallow, but additional warm moist air from the urban surface was available. The moist inflow for system B was deep in association with the southeastern part of the major arc-shaped moist tongue in the confluent marine southeasterlies. The dynamic lifting to trigger system A was attributed to the enhancement of southeasterlies with local orographic lifting south of the Huadu hills, while that to trigger system B was mainly led by the northerly cold-pool outflows colliding with the southeasterlies.

Previous studies of the same case have also discussed these dynamic and thermodynamic processes. Their focused perspectives are different, for example, the impacts of urbanization and topography (Yin et al. 2020), land surface processes (Gao et al. 2021), microphysical processes based on multisource observations (M. Li et al. 2020) and the comparison of microphysics parameterization schemes in WRF (Huang et al. 2020). Our study showed the roles of multiscale factors in nocturnal CI processes and their interactions. The intruding synoptic-scale marine southeasterlies appeared to establish a background for the initiation and growth of the two convective systems. The mesoscale processes associated with the southeasterlies play a role in the following three aspects. First, in the dynamic aspect, the mesoscale lifting at the leading edge of the southeasterlies combines with the local orographic ascents of the Huadu hills prior to CI, which provides lifting for CI and largely influences the timing and location of system A. Second, from a thermodynamic perspective, the mesoscale moistening of the southeasterly moist tongue is combined with the local urban heating of Guangzhou city to strengthen potential instability for the growth of system A. Third, in terms of convection feedback, the mesoscale moist tongue collides with the convectively induced cold pool to sustain local and long-lived convective systems. These local factors, including orographic lifting, urban heating, and convectively induced cold pools, seemed to work in different stages of triggering and supporting the convective systems. We further examined the detailed roles of the low-level moist tongue in the southeasterlies and urban near-surface warm moist air being lifted in the next section.

5. Sensitivity of CI to low-level moist southeasterlies and local surface conditions

In this section, we detail the conducted sensitivity tests to examine the key factors and to quantify their relative contributions to the nocturnal convective system. As indicated, one key factor was the moist tongue of low-level southeasterlies from the northern SCS. Its structure and impact on convection can be numerically changed with or without nudging the sounding data (especially the upstream sounding profile at Hong Kong) at the initial time. Another key factor was urban heating, which can be changed with or without nudging local surface observations around Guangzhou. Specifically, the model results shown in sections 3–4 (named the CTL run) were nudged both the sounding data and local surface observations, giving an improved modeling of the combined effects of the low-level southeasterly moist tongue and local conditions over Guangzhou. In addition to the CTL run, we further conducted three sensitivity tests (named EXP0–2), which are summarized in Table 1. In the EXP0 run, there was no nudging of sounding data and local surface observations. The EXP0 run indicates a “normal” simulation without data assimilation. Compared to EXP0, the CTL run gives an improved simulation of the combined effects of the low-level southeasterly moist tongue and local conditions over Guangzhou. In the EXP1 run, only the sounding data were nudged, which mainly improves the modeling of the moist southeasterlies compared to the EXP0 run. In the EXP2 run, only the surface observations around Guangzhou were nudged to improve the representation of local thermal conditions. The model configurations introduced in section 2b were applied in all four runs. Here, we compare CTL and EXP1–2 with EXP0 (as a reference without data nudging) to clarify how the two factors contribute to CI and convective growth.

All three runs captured the initiation of convection A near the Huadu hills from 0020 to 0120 LST based on the simulated radar reflectivity (Figs. 11a,b,e,f,i–j). The new convective cells were mostly located to the north of the hills in EXP0 and EXP2, but some cells occurred to the south of the hills in EXP1. In the following hours of convective growth (from 0220 to 0320 LST), the convective cells remained north in EXP0 and EXP2 (Figs. 11c,d,k,l), while they can develop southeastward to eastern Guangzhou in EXP1 (Figs. 11g,h). The CI and convective growth to the south of the hills in EXP1 were similar to convective system A in the CTL run and radar observations but presented a weaker intensity
These differences between EXP1/CTL and EXP0/EXP2 suggested that the nudging of sounding data (related to the moist southeasterlies) improved the modeled moisture (the amount, structure, and local distribution), which was crucial for improving the simulation of the convection over the Guangzhou regions to the south of the hills.

We further examined the combined effects of the low-level moist southeasterlies and local thermal conditions over Guangzhou by comparing CTL with EXP0. The intruding southeasterlies in EXP0 were strengthening at night with convergence and associated lifting at their leading edge to the south of Huadu hills (Figs. 12a–e). These features were analogous to those in CTL, indicating that the dynamic conditions were less changed (cf. Figs. 2, 6, and 11).
As the Froude number near the Huadu hills was less than 1, the southeasterlies were mainly blocked by the hills in both runs, which allowed the warm moist air to be enhanced prior to CI. However, $u_e$ was less than 348 K below 1.5 km AGL, which was smaller in EXP0 than in CTL or the other experiments (Figs. 12a–e). Therefore, the nudging procedure mainly changed the thermal properties rather than the dynamic lifting to the south of the hills, which seemed to be responsible for the difference in CI between the EXP0 and CTL runs herein. The large differences in $u_e$ between CTL and EXP0 are further shown in Figs. 12f–j. The increases in $u_e$ in the CTL were estimated as 4–6 K in the lower troposphere below 1.5 km AGL and as 6–8 K near the surface below 300 m AGL. These differences manifest the combined effects of the low-level southeasterly moist tongue and urban thermal conditions on triggering convection to the south of the Huadu hills. The near-surface warm moist air from the urban area was elevated into the lower troposphere at the leading edge of the southeasterlies since 0120 LST, thereby fueling convective growth (Figs. 12h–j).

We then quantify the individual contributions of the low-level southeasterly moist tongue and the near-surface local thermal conditions. Figures 12k–o show the effects of nudging sounding data based on the differences between EXP1 and

![Fig. 12](image-url)
EXP0. An increase in $\theta_v$ (4–6 K) was found at 0.3–1.5 km AGL in the lower troposphere. It corresponded to an improved representation of the southeasterly moist tongue due to the nudging of sounding data, which played a key and more important role in simulating the convection systems, especially the CI to the south of the hills. Figures 12p–t show the changes in $\theta_v$ due to the nudging of local surface observations over Guangzhou. This explained the increase in $\theta_v$ (4–6 K), mainly near the surface in EXP2. The enhanced high-$\theta_v$ air was then lifted to ~1 km height at the leading edge of the southeasterlies during the hours of convective growth (Figs. 12r–t). However, it was not enough to trigger convection because of a lack of warm moist air in the lower troposphere in EXP2.

The urban thermal effect can also be shown by the differences between CTL and EXP1. The local surface observation over the Guangzhou region was nudged in the CTL run but not in EXP1, while the sounding data had already been nudged in both runs to capture the lower-tropospheric moist tongue. The CTL run has a marginally improved simulation of the radar reflectivity (the timing, location, and intensity of the convective system A) and the near-surface environmental conditions over urban Guangzhou compared to EXP1, suggesting that the urban near-surface warm moist air being lifted by the southeasterlies into the lower troposphere partly improved the modeled convective growth. Therefore, the moist tongue of low-level southeasterlies is crucial for supporting CI and convective growth, while the urban thermal conditions also play a role in strengthening the convection in the downstream Guangzhou regions.

Previous studies have discussed the dynamic and thermodynamic processes in this heavy rain event from different perspectives. Huang et al. (2019a,b) emphasized that the lower-tropospheric moist southeasterly inflows provide the crucial energy to fuel convection. Yin et al. (2020) highlighted that the strong urban heating in the Guangzhou region was the main contributor to CI, fueling important energy downstream of marine southeasterlies. Y. Wu et al. (2021) suggested that the small-scale Huadu hills played a crucial role in the CI. The katabatic northerly winds induced by the nighttime cooling of the Huadu hills converged with the southeasterlies to enhance the convergence south of the hills. Gao et al. (2021) pointed out that slight variations in small-scale land surface conditions may lead to changes in total rainfall. As indicated, our study proposed a generalized concept in which the inland intrusion of synoptic-related southeasterlies provides a key environment for all these factors working together. The enhanced low-level southeasterlies at night correspond to the timing of nocturnal convection inland. The urban near-surface energy is carried by the low-level ascent at the leading edge of the southeasterlies into convection, locally participating in convective development. The arc-shaped mesoscale moist tongue of the southeasterlies from the SCS and its collision with the outflows of the cold pool continue to fuel the locally cold-pool-related ascents, sustaining the long-lived convective system. Therefore, the combined effects of all these processes explain the local but long-lived convective systems at night in the warm-sector inland regions, which produce record-breaking heavy rainfall.

6. Conclusions and discussion

In this study, we examine local and long-lasting convective systems that led to record-breaking warm-sector heavy rainfall in the inland regions of South China. We clarify the physical processes leading to the nocturnal CI and convective growth using intense observations and convective-permitting model results. A conceptual model is proposed in Fig. 13 to summarize the key processes. The major findings are listed as follows.

1) Observational analyses show that the heavy rainfall event occurs in the warm-sector inland regions under a relatively weak forced background at 500 and 850 hPa over South China. The synoptic-scale pattern is characterized by a high pressure system over Central China and moderate but strengthening low-level southeasterlies from the northern South China Sea (SCS) as a result of inertial oscillation. It is different from the other warm-sector rainfall events that usually feature strong monsoon southwesterlies or low-level vortices over South China. The confluent southeasterlies with a depth of ~1000 m lead to an arc-shaped mesoscale moist tongue extending from the SCS to the Guangzhou region. The inland intrusion of the southeasterlies with the moist tongue corresponds well to the convective system that locally develops in the north inland of Guangzhou city. A convective system A is first initiated when the leading edge of the southeasterlies arrives south of Huadu hills and is followed by another system B adjacent to the southeast with a lag of ~2 h as well as back-building system C thereafter. These convective systems are quasi-stationary and produce two local maxima of heavy rainfall in northern and eastern Guangzhou.

2) The convection-permitting simulation reproduces the initiation/growth of convective system A and succeeding systems B and C as well as their associated atmospheric conditions. The nocturnally enhanced southeasterlies provide low-level convergence and lift at their leading edge as they intrude inland. Mesoscale lifting is enhanced by the local orographic ascents of the Huadu hills prior to CI, which supplies dynamic conditions for CI and largely influences the timing and location of system A. The mesoscale moist tongue, intruding inland with the southeasterlies, strengthens low-level moisture. The warm moist air from the urban surface of Guangzhou city is carried and lifted by the southeasterlies into the lower troposphere, producing potential instability. Mesoscale moistening is thus locally combined with urban heating, establishing thermodynamic conditions favorable for nocturnal CI. Approximately 2 h after CI, the mature system A produces a cold pool with northerly outflows to its southern/eastern sides. The convective updrafts ahead of the cold pool continue to fuel system A with the remaining warm moist air from the south. Additionally, the new system B develops adjacent to the east of system A, where the mesoscale moist tongue collides with the outflows of the convectively induced cold pool to sustain strong updrafts and support
3) We conduct sensitivity tests to further estimate the relative roles of the southeasterly moist tongue and local thermal conditions in the CI processes. The two factors can be numerically changed by nudging the sounding data (especially upstream stations at Hong Kong) or the surface observations. The nudging of these data mainly results in an increase in $\theta_e$ (approximately 6 K) in the low-level moist tongue and in the urban surface layer. The nocturnal convective systems at Guangzhou can be reproduced by the experiments by nudging the sounding data in the moist tongue. The differences among these runs highlight that the southeasterly moist tongue plays a crucial role in the initiation and growth of the convective system. The timing, location and intensity of the simulated convective system are further improved if the surface observations at Guangzhou are also nudged. This suggests that the near-surface warm moist air can be lifted by the southeasterlies to fuel the growth of system A so that the urban heating at Guangzhou provides additional energy for convective growth. The increased $\theta_e$ value from the urban surface can be locally comparable to that from the low-level southeasterly moist tongue. These two factors can be combined through the enhanced convergence at the leading edge of the southeasterlies to support the local intense convection.

As some key features in this event are distinct from those previously revealed for the typical events of warm-sector heavy rainfall events over South China, further studies are therefore needed to address the following aspects. First, a key issue involves the different types of onshore flows that influence nocturnal CI, with moderate southeasterlies prone to inland CI and strong monsoon southwesterlies (mostly LLJs) prone to coastal CI (Du and Chen 2019; Zhang and Meng 2019; N. Wu et al. 2020b; Y. Wu et al. 2020a; Du et al. 2020a; Wang et al. 2021). An estimation of regional forcing, such as boundary layer inertial oscillation under different synoptic patterns, may aid in clarifying the formation of nocturnally enhanced onshore flows and their impacts on other heavy rainfall events. Second, the localized extreme rainfall in coastal or urban areas is another issue deserving further analyses (M. Wu et al. 2019; Sun et al. 2021). This study proposed that a mesoscale moist tongue combined with local urban/orographic effects led to a confined pattern of potential instability that greatly supported localized but long-lived convection. An objective identification of the mesoscale moist tongues in South China or other coastal areas may help to clarify their interactions with urban or orographic effects for producing intense rainfall events.
As the warm-sector nocturnal CI is closely related to complex interactions among multiscale processes, it corresponds to a low predictability of the heavy rainfall over South China. A key issue involves the uncertainty in the modeling of low-level orographic effects, urban heating, and cold pools (Zhang and Meng 2019; Shen et al. 2020; Du et al. 2020a). This study and previous ones found that a better representation of both marine inflows and local conditions on land through data assimilation leads to an improved simulation of the CI for warm-sector rainfall events (Huang et al. 2019b; Yin et al. 2020; Y. Wu et al. 2020b; Du et al. 2020b). However, as the observations are sparse offshore of the SCS, it is still a challenge to describe the structures and variations in winds and moisture in the marine boundary layer (Luo et al. 2020). Future studies exploring offshore observation network data, despite limited availability, are needed to reduce the uncertainty in modeling the nocturnal CI in both inland and offshore areas of South China.

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Data availability statement. The Climate Prediction Center morphing technique (CMORPH) data are openly available from NOAA/Climate Prediction Center (ftp://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/CRT/8km-30min/) as cited in Joyce et al. (2004). The hourly ERA5 are openly available from ECMWF (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview) as cited in Hersbach et al. (2020). The National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data are available online by NCAR’s Data Support Section at http://rda.ucar.edu/datasets/ds083.2/. The hourly surface observations are provided by the China Meteorological Administration at http://data.cma.cn. The modeling results are the output using the Advanced Weather Research and Forecasting (WRF) Model v3.9.1, which can be reproduced using the setup described in this paper.

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