



- Spatiotemporal Characteristics and Environmental Controls of Non-Typhoon Mesoscale Convective Systems during the Post-flood Rainy Season over South China

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Abstract. South China is one of China's rainiest regions, where mesoscale convective systems (MCSs) frequently produce heavy rainfall during the post-flood rainy season (July-September). Using 1-km, 6-min radar mosaics and ERA5 reanalysis, this study identified 123 MCSs from 2019 to 2022. MCS activity is concentrated over southern Guangxi (S-GX) and the Pearl River Delta (PRD), with marked regional contrasts in diurnal evolution and environmental conditions. Variations in the relative positions of the South Asian High (SAH) and the western North Pacific subtropical high (WNPSH) produce distinct circulation regimes over the two regions. S-GX MCSs over the S-GX mainly form from midnight to early morning and are associated with an eastward-extended SAH and a westward-displaced WNPSH, which strengthen the southerly monsoonal flow and produce a deeper moisture transport layer extending to approximately 750 hPa. Together with larger convective instability (mean CAPE $\approx 1843 \text{ J kg}^{-1}$), these conditions allow convection to overcome the relatively larger convective inhibition (CIN) and support nocturnal MCS development. In contrast, PRD MCSs over the PRD mainly form from afternoon to evening under weaker large-scale forcing, shallower moisture transport largely confined below 900 hPa, lower but localized instability (mean CAPE $\approx 1523 \text{ J kg}^{-1}$) and smaller inhibition. These conditions increased the relative importance of daytime boundary-layer heating and sea-breeze convergence, consistent with the afternoon to evening MCS maximum. The results identify a synoptic-dynamical mode over S-GX and a boundary-layer thermodynamic mode over the PRD, providing a physical framework for understanding post-flood-season MCS development and heavy rainfall over South China.

Key Words. Non-typhoon mesoscale convective systems; Large-scale circulation; Environmental conditions; Post-flood rainy season; South China



1 Introduction

South China (SC), located along the southern coast of China (Fig. 1) and bordering the South China Sea (SCS), is one of the rainiest regions in China, with annual precipitation exceeding 2000 mm in some areas (Ding and Chan, 2005; Luo et al., 2017). Most annual rainfall occurs during the warm season, which is commonly divided into the pre-summer rainy season (April-June) and the post-flood rainy season (July-September) (Wang and Ding, 2008; Li et al., 2021). During the pre-summer rainy season, heavy rainfall over SC is primarily associated with frontal systems, shear lines, and the monsoonal southwesterlies, whereas post-flood-season rainfall is more strongly influenced by tropical circulation systems, the western North Pacific subtropical high (WNPSH), and the seasonal evolution of the East Asian summer monsoon (Luo et al., 2020). Tropical cyclones (TCs) are traditionally regarded as major contributors to post-flood rainy season rainfall over SC because of their extensive circulation, persistent moisture transport, and long-lasting precipitation footprints. Nevertheless, the contribution of TCs to event-total or seasonal accumulated rainfall does not necessarily represent their role in short-duration rainfall extremes. Luo et al. (2016) showed that a substantial proportion ($> 50\%$) of extreme hourly precipitation events over SC occurred under non-TC synoptic conditions, including fronts, vortices or shear lines, and weak synoptic forcing. Other climatological studies further identified numerous persistent heavy rainfall events during the post-flood season that were not directly associated with TCs, together with diverse large-scale circulation patterns responsible for TC-independent precipitation extremes (Liu et al., 2016; Wu et al., 2016; Li et al., 2017). These findings indicate that non-TC systems make a substantial contribution to heavy rainfall during the post-flood rainy season, particularly to extremes occurring on hourly to sub-daily timescales.

Among non-TC precipitation-producing systems, mesoscale convective systems (MCSs) play a dominant role in generating short-duration extreme rainfall and flash-flood hazards worldwide (Nesbitt et al., 2006; Roca et al., 2014; Schumacher and Johnson, 2005; Utsumi et al., 2017; Schumacher and Rasmussen, 2020; Taszarek et al., 2021; Haberlie & Ashley, 2022; Zhao et al., 2022). Globally, MCSs contribute more than half of tropical precipitation and account for a large fraction of extreme rainfall events because of their organized structures, high precipitation efficiency, long lifetimes, and propagation capability (Davis, 2001; Houze, 2004). Over SC, MCSs are also recognized as major contributors to warm-season precipitation. Wang et al. (2025) showed that MCSs contribute approximately 65% of warm-season rainfall along the southern coast of China, while Fu et al. (2024) demonstrated that MCSs contributed more than half of the rainfall during the 2022 South China Dragon Boat Rainy Season. These studies highlight the critical role of MCSs in producing high-impact precipitation over SC and motivate further investigation of their regional characteristics and environmental controls.

MCS properties exhibit strong regional dependence because they are regulated by different monsoonal regimes, synoptic environments, and topographic conditions (Peters and Schumacher, 2014; Punkka and Bister, 2015; Roy and Saha, 2026). Seasonal contrasts in MCS environments have also been documented. Over the U.S. Great Plains, Song et al. (2019) showed that spring MCSs are commonly associated with frontal lifting and enhanced low-level moisture transport, whereas summer MCSs can develop under weaker large-scale dynamical and thermodynamic perturbations. Across China, previous studies



have identified substantial regional differences in MCS organization and evolution. Over central-eastern China, MCSs are strongly influenced by mei-yu fronts and monsoonal circulation, with diverse linear and nonlinear organizational modes (Zheng et al., 2013; Wang et al., 2014). Over North and Southwest China, MCS development is additionally modulated by midlatitude disturbances, low-level jets, terrain-induced circulations, and complex topography (Ueno et al., 2011; Ma et al., 2021; Meng et al., 2021; Long et al., 2023). Considerable progress has also been made in documenting MCSs over SC, particularly during the pre-summer rainy season. Using 6-min, 1-km radar mosaics, Chen et al. (2022) analysed 98 quasi-linear MCSs during 1 May–15 June of 2013–2017 and identified pronounced regional differences in genesis timing, movement, mature-stage organization, and synoptic-scale environment. Li et al. (2021) further documented the diversity of organizational modes among MCSs associated with warm-sector heavy rainfall over SC. More recently, Yu et al. (2026) and Pu et al. (2026) further quantified the spatial and temporal characteristics of convection initiation associated with warm-sector heavy rainfall. Together, these studies provide a detailed picture of pre-summer MCS morphology, initiation, and evolution over SC.

The initiation, organization, and maintenance of MCSs depend on the interaction of atmospheric moisture, instability, lifting mechanisms, and vertical wind shear (Doswell et al., 1996; Schumacher and Rasmussen, 2020; Muetzelfeldt et al., 2025). During the pre-summer rainy season over SC, synoptic disturbances modulate the moisture supply and ascending motion associated with extreme rainfall (Huang et al., 2018), while low-level jets contribute to moisture transport and convergence supporting convective development (Liu et al., 2020; Li and Du, 2021). Near the coast, convection initiation and upscale growth are further regulated by the interactions of onshore flow with land–sea-breeze circulations, coastal orography, boundary-layer convergence, and convectively generated cold pools (Du et al., 2020; Bai et al., 2020; Huang et al., 2022,2024; Pu et al., 2026).

In contrast, MCS development during the post-flood rainy season occurs under substantially different large-scale circulation conditions. The northward migration of the monsoon rainband and the associated reorganization of regional circulation modify the thermodynamic and dynamical environment over SC. Besides TCs, post-flood-season convection may be influenced by tropical and subtropical disturbances, including the WNPSH, monsoon trough, intertropical convergence zone, low-level vortices, shear or convergence zones, and easterly disturbances (Ding and Chan, 2005; B. Wang et al., 2009; Li et al., 2021). Local processes, such as land–sea-breeze convergence, coastal and inland topography, and diurnally varying boundary-layer processes, may further trigger and organize convection. For example, SCS easterly waves have been shown to promote onshore convection over coastal SC (Chen and Yuan, 2022). However, the relative importance of these circulation systems and their impacts on non-TC MCSs characteristics during July–September remain poorly quantified. Accordingly, this study conducts a four-season statistical investigation of non-TC MCSs over SC during the post-flood seasons of 2019–2022. Section 2 describes the data and methods. Section 3 documents the occurrence frequency, spatial distribution, genesis timing, lifetime, and propagation characteristics of non-TC MCSs, with particular emphasis on regional differences, and further examines the large-scale circulation regimes and the thermodynamic and dynamical environments associated with MCS initiation and development. The main conclusions are summarized in Section 4.



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2 Data and method

2.1 Data

In this study, MCSs were identified using composite radar reflectivity mosaics with a spatial resolution of 1 km and a temporal resolution of 6 min. The mosaics were generated by the Doppler Weather Radar Three-Dimensional Digital
105 Networking System developed by the Chinese Academy of Meteorological Sciences (H. Wang et al., 2009), which performs quality control and merges operational Doppler weather radar observations into seamless composite products. The gridded radar mosaics in this study were derived from 26 S-band Doppler weather radars (Fig. 1) covering South China during the post-flood rainy season. These radars are comparable to the Weather Surveillance Radar-1988 Doppler (WSR-88D) network used in the United States in terms of both hardware and software. Radar mosaic products generated by this networking
110 system have been widely used in studies of heavy rainfall and other severe weather events in China (e.g., Luo et al., 2014; Wang et al., 2014; Liu et al., 2018; Chen et al., 2022; Hu et al., 2025).

To determine whether an MCS was associated with a tropical cyclone (TC), we used the tropical cyclone best-track dataset provided by the China Meteorological Administration (CMA) (Ying et al., 2014; Lu et al., 2021; <https://tcdata.typhoon.org.cn/zjljsjj.html>). The dataset covers tropical cyclones over the western North Pacific, including the
115 South China Sea, and provides six-hourly information on each TC, including its name, centre position, central pressure, and maximum sustained wind speed.

The ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020) was used to characterize the synoptic environment associated with MCS development. The dataset has a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and an hourly temporal resolution.

120 2.2 MCS identification and tracking

Using the composite radar reflectivity data, MCSs were identified through a combination of objective criteria and manual inspection. Following criteria widely adopted in recent studies in China (e.g., Meng et al., 2013; Li et al., 2021; Chen et al., 2022), an MCS was defined as a continuous area with strong radar reflectivity (≥ 40 dBZ) with a maximum horizontal extent of at least 100 km and a duration of at least 1 h. Based on these criteria, a total of 123 MCSs were identified from 88,316
125 radar images at 6 min intervals during July–September of 2019–2022.

The identified MCSs were further classified according to their association with TCs using the CMA tropical cyclone best-track dataset. To exclude potential TC influences prior to MCS formation, an MCS was classified as TC-associated if the centre of a TC that subsequently reached at least tropical-depression intensity ($\geq 10.8 \text{ m s}^{-1}$) was located within 500 km of any grid point in the study domain during the 6 h preceding MCS formation time. MCSs that experienced TC influence after
130 their formation, as well as the remaining events, were classified as non-TC MCSs. The present study focuses exclusively on



non-TC MCSs, of which 72 were identified during the study period. Hereafter, for brevity, “MCS” is used to refer to non-TC MCSs unless otherwise specified.

The MCS life cycle was defined as the period from initiation to dissipation. The initiation time was defined as the first appearance of a radar echo with reflectivity ≥ 40 dBZ. The dissipation time was defined as the first time at which no radar echo with reflectivity ≥ 40 dBZ remained within the MCS or the system moved outside the study domain (106–117°E, 20–26°N; Fig. 1). Moreover, the formation time of an MCS was defined as the first time at which a contiguous region of radar reflectivity ≥ 40 dBZ reached a horizontal extent of at least 100 km in any direction.

2.3 Selection of Similar Synoptic Pattern Days for MCSs

The date on which at least one MCS (no MCS) occurs within the analysis region (as shown by the dashed box in Fig 1) is defined as an MCS (non-MCS) day. During the analysis period, there are 62 MCS days.

To further investigate the synoptic environmental conditions associated with MCS occurrence, non-MCS days characterized by circulation patterns similar to those on MCS days were identified. The 925 hPa geopotential height field at 1600 LST (LST = UTC + 8 h), representing the daily circulation pattern, was selected to classify weather backgrounds during the post-flood rainy season over SC, as MCS activity reaches its peak frequency at this time. A composite circulation field was first constructed by averaging the 925 hPa geopotential height fields across all MCS days, representing the typical large-scale circulation background associated with MCS occurrence. The circulation pattern of each non-MCS day was then compared with this composite field using the Euclidean distance and spatial correlation coefficient. Non-MCS days with similar circulation backgrounds were identified when their Euclidean distances fell within the lowest 40% and their spatial correlation coefficients fell within the highest 60% among all candidate days. Based on these criteria, 56 matched non-MCS days with circulation patterns similar to those of MCS days were identified. Comparisons of weather backgrounds between MCS and matched non-MCS days were then conducted to investigate the large-scale dynamical and thermodynamic conditions regulating convective development. Hereafter, for brevity, “non-MCS days” is used to refer to the 56 matched non-MCS days unless otherwise specified.

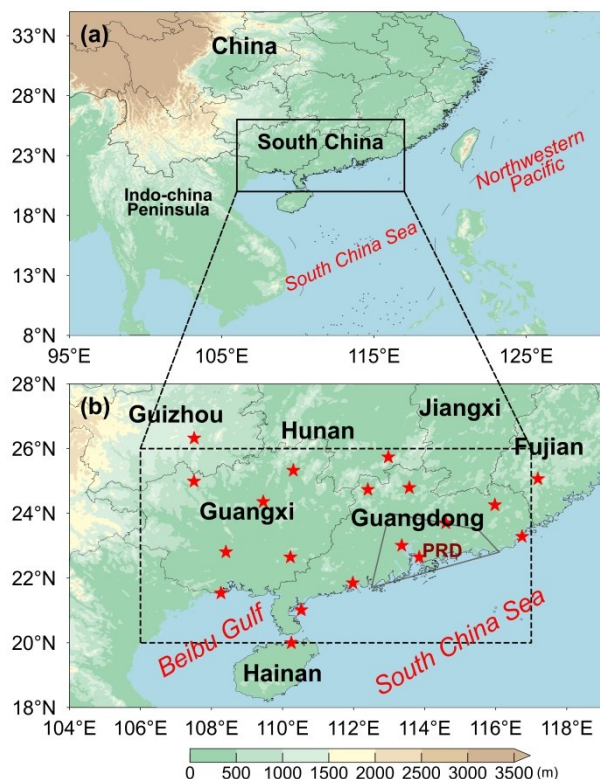


Figure 1: Topography map over East and Southeast Asia (a) and the South China (SC) region (b). Provincial boundaries and the locations of operational radar stations (red stars) are shown in (b). Shadings represent the terrain elevation (m). The grey solid outline indicates the Pearl River Delta (PRD) region. The dashed box denotes the analysis region (106–117°E, 20–26°N) for the identification and analysis of post-flood rainy season MCSs.

3 Results

3.1 Spatiotemporal distributions of the MCSs

The spatial distribution of MCSs identified during the study period is shown in Figure 2. The initiation and formation frequencies of MCSs exhibit pronounced spatial heterogeneity across SC (Fig. 2a, b). Two prominent MCS activity centres are identified over the Pearl River Delta (PRD) and southern Guangxi (S-GX, approximately south of 23°N), where the formation frequencies reach their maxima. Compared with initiation locations, MCS formation locations exhibit a more concentrated pattern, suggesting that initiated convection tends to organize into MCSs along preferred pathways characterized by favourable dynamical and thermodynamic environments. The track-density distribution further confirms that MCS activity is primarily confined to two preferred corridors extending from S-GX and the PRD (Fig. 2c). Based on this spatial separation, the study region was divided at 111.2°E into western and eastern subregions. For consistency with the spatial representation in the figures, MCSs occurring in the western and eastern subregions are hereafter referred to as S-GX MCSs and PRD MCSs, respectively.

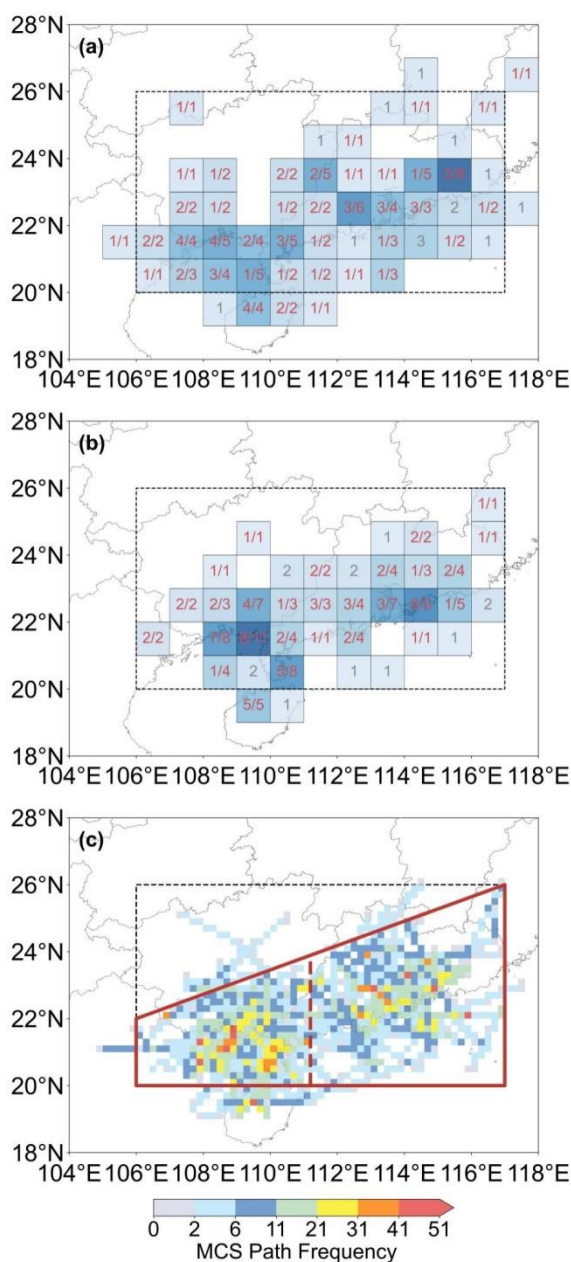


Figure 2. (a) Convective initiation (the first echo) and (b) formation locations of MCSs within each 1°×1° grid box. The numbers indicate the occurrence frequency of MCSs within each grid box. When both non-TC MCSs and TC-related MCSs types occur within the same grid box, the values are shown as non-TC MCSs/total MCSs, with the numerator representing the number of non-TC MCSs and the denominator representing the total number of identified MCSs. A single red (gray) number indicates that all identified MCSs in that grid box are non-TC (TC-related) MCSs. (c) Track density of non-TC MCSs from initiation to dissipation within each 0.1°×0.1° grid box. The red rectangle indicates the domain used to calculate the environmental parameters in Fig. 5. The red dashed line at 111.2°E separates the western and eastern subregions. Shading represents non-TC MCSs track frequency.



Compared with the pre-summer rainy season MCSs documented by Chen et al. (2022), MCSs activity during the post-flood rainy season in SC tends to be more concentrated along the coastal regions, suggesting that seasonal changes in large-scale circulation and moisture transport may regulate the preferred locations of MCS initiation and organization.

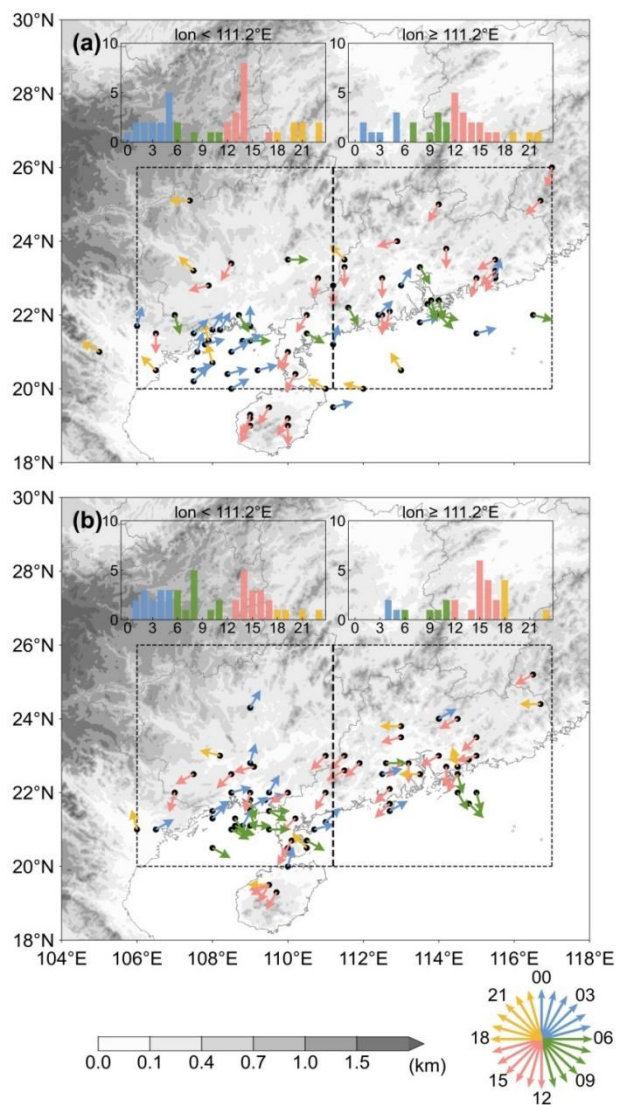


Figure 3. Times and locations of non-TC MCSs (a) initiation and (b) formation. Black dots indicate MCSs initiation or formation locations, and colored arrows represent the occurrence time (local standard time, LST; UTC+8) of individual MCSs. The inset histograms show the diurnal distributions of MCSs initiation and formation times in the western ($< 111.2^\circ\text{E}$; S-GX) and eastern ($\geq 111.2^\circ\text{E}$; PRD) subregions. Shadings denote the terrain elevation (km), the gray lines indicate provincial boundaries and coastlines, and the dashed rectangle outlines the analysis region.

The initiation and formation times of non-TC MCSs during the post-flood rainy season exhibit pronounced regional differences over SC (Fig. 3a, b). Overall, MCS activity shows a clear diurnal cycle, but the preferred timing varies



substantially among regions. In the PRD, MCSs formation exhibits a pronounced afternoon peak, with the maximum occurring during 12:00–17:00 LST. The afternoon maximum in PRD is consistent with previous studies showing that convective initiation over coastal SC frequently peaks in the afternoon, when enhanced surface heating promotes boundary-layer development, thermal instability, and local convective activity (Fu et al., 2024; Su et al., 2025).

In contrast, MCSs over S-GX exhibit a bimodal diurnal distribution, with a peak from midnight to early morning and a peak in the afternoon. The nighttime-to-morning peak indicates a higher frequency of MCSs initiation and formation during the nocturnal period, whereas the afternoon peak suggests that locally driven convection also contributes to MCSs development. Compared with the PRD, the earlier and more pronounced nocturnal activity over S-GX highlights the greater importance of processes beyond daytime surface heating, including regional circulation, moisture transport, and mesoscale dynamical forcing. These regional contrasts suggest that non-TC MCSs development during the post-flood rainy season is governed by distinct combinations of local thermodynamic conditions and larger-scale dynamical environments.

3.2 Large-scale environments associated with MCS occurrence

The composite circulation patterns during the post-flood rainy season reveal distinct large-scale environments associated with MCS occurrence over SC (Fig. 4). Although MCS and non-MCS days exhibit similar low-level circulation patterns, MCS days are characterized by a more favourable convective environment, with enhanced mid-tropospheric ascent, stronger low-level moisture convergence, and increased atmospheric instability.

At 500 hPa (Fig. 4a), SC is located within a southwesterly flow regime downstream of the Tibetan Plateau and ahead of a weak trough, providing a favourable large-scale dynamical background for convection development. Pronounced ascending motion is observed over SC during MCS days, with vertical velocity reaching approximately -0.02 to -0.03 m s^{-1} . Compared with non-MCS days, the magnitude of mid-tropospheric ascent is enhanced by approximately 0.01 m s^{-1} (Fig. 4d), indicating that upward motion during MCS events is roughly twice as strong as that under non-MCS conditions. In the lower troposphere (925 hPa; Fig. 4b), MCS days are characterized by enhanced southwesterly moisture transport from the northern SCS and pronounced convergence over SC. The low-level convergence associated with MCS days reaches approximately -4×10^{-6} to -8×10^{-6} s^{-1} , substantially stronger than that on non-MCS days (Fig. 4e). The enhanced convergence overlaps well with the regions of frequent MCS occurrence (Fig. 2), highlighting the importance of low-level dynamical convergence and moisture transport in supporting convection.

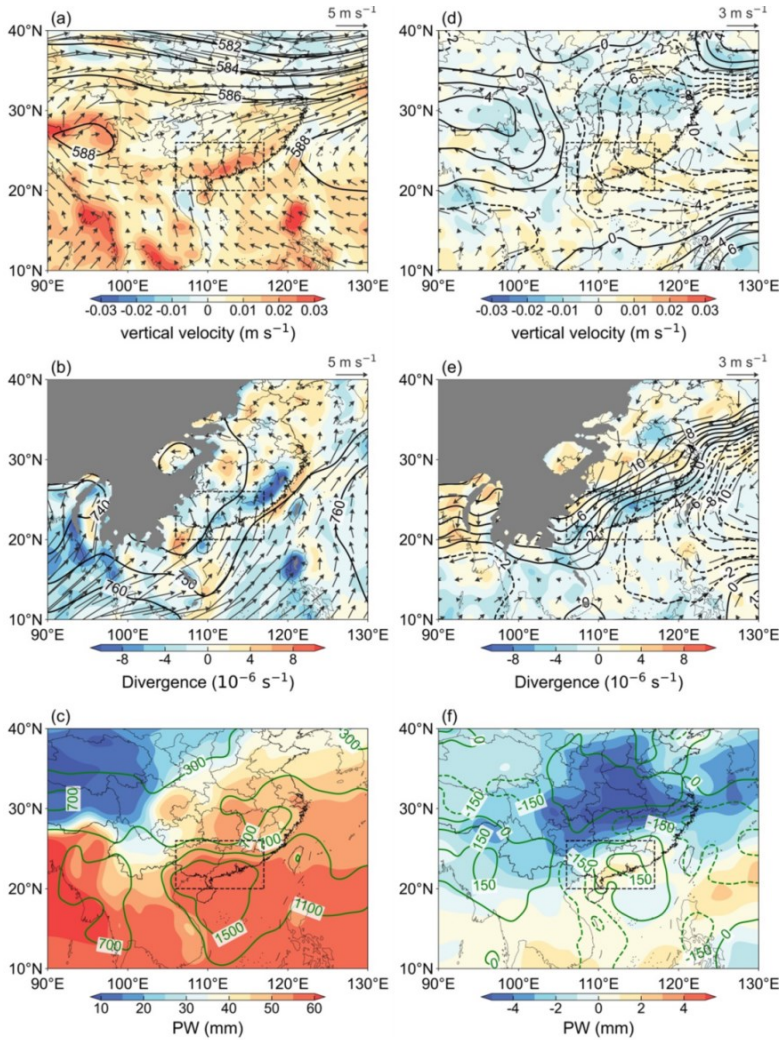


Figure 4. Composite circulation patterns associated with MCS formation. (a–c) Composite fields on MCS days and (d–f) differences between MCS days and non-MCS days (MCS minus non-MCS). (a, d) 500 hPa horizontal winds (black arrows; m s^{-1}) and geopotential height (black contours; m), with shading indicating vertical velocity (m s^{-1}). (b, e) 925 hPa horizontal winds (black arrows; m s^{-1}) and geopotential height (black contours; m), with shading showing horizontal divergence (10^{-6} s^{-1}). (c, f) Convective available potential energy (CAPE; contours; J kg^{-1}) and precipitable water (shading; mm). Gray lines denote provincial boundaries and coastlines. The dashed rectangle indicates the analysis region ($106\text{--}117^\circ\text{E}$, $20\text{--}26^\circ\text{N}$).

The vertical structures of divergence and vertical motion further demonstrate the vertically coupled dynamical characteristics associated with MCSs occurrence (Fig. 5). During MCS days, strong low-level convergence is observed below approximately 900 hPa and extends upward into the middle troposphere. The flow gradually transitions to strong upper-level divergence above approximately 300 hPa, forming a vertically coupled circulation pattern favourable for organized convection (Fig. 5a). Compared with non-MCS days, the difference profiles show enhanced low-level convergence and upper-level divergence, with the largest contrast occurring near the lower tropospheric convergence layer and around 200 hPa (Fig. 5b). Consistent with the divergence structure, enhanced ascending motion extends through the entire tropospheric



column during MCS days, with maximum values reaching approximately 0.02 m s^{-1} near 200–300 hPa. Compared with non-MCS days, stronger ascent is evident throughout the middle and upper troposphere (Fig. 5d), indicating a deeper and more vertically coupled circulation structure during MCS occurrence.

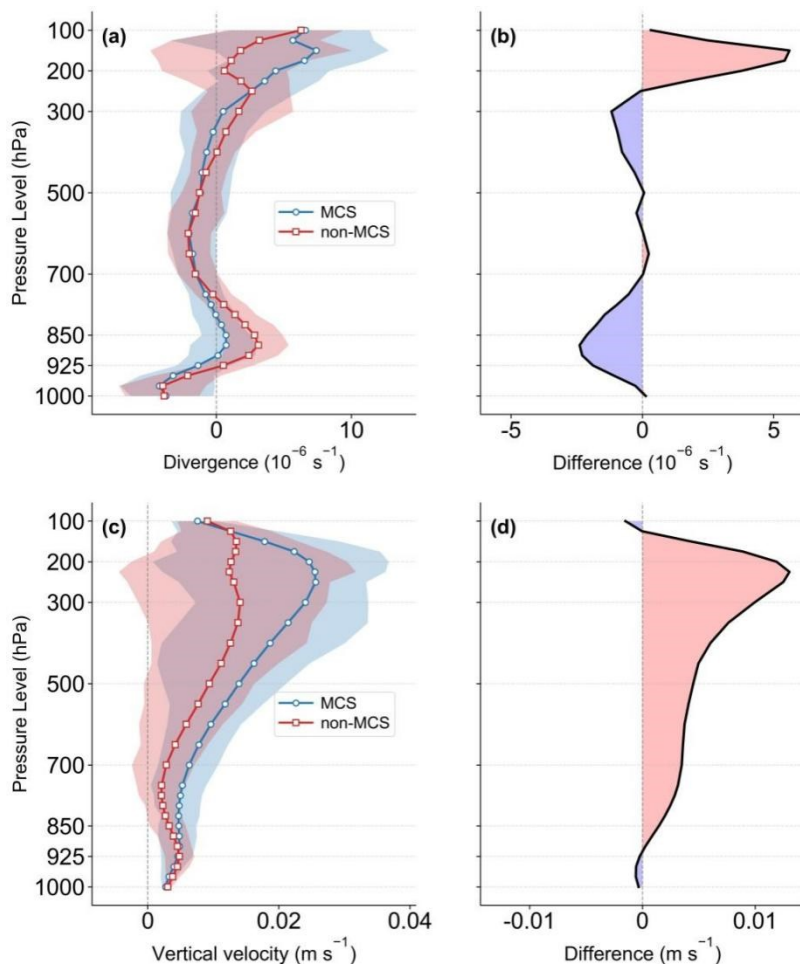


Figure 5. Vertical profile of divergence and vertical velocity associated with MCS events. (a) Divergence (10^{-6} s^{-1}) and (c) vertical velocity (m s^{-1}) for MCS days (blue lines) and non-MCS days (red lines), respectively. Solid lines represent the mean vertical profiles, and the shaded areas denote the interquartile range. (b) Divergence and (d) vertical velocity difference between MCS days and non-MCS days (MCSs days minus non-MCS days). The divergence and vertical velocity profiles are calculated over the red outlined region shown in Fig. 2c.

In addition to the dynamical conditions, thermodynamic instability also plays an important role in supporting MCSs development. During MCS days, CAPE exceeds 1500 J kg^{-1} over much of SC and locally approaches 2000 J kg^{-1} (Fig. 4c), indicating a highly unstable environment. Meanwhile, PW remains high across the study region, exceeding approximately 60 mm, suggesting abundant moisture availability. Compared with non-MCS days, CAPE and precipitable water (PW) are both



enhanced during MCS events (Fig. 4f), suggesting that sufficient moisture supply combined with strong convective
 250 instability provides favourable thermodynamic support for MCSs initiation and organization.

Overall, post-flood-season MCSs occurrence over SC is associated with the coexistence of enhanced low-level moisture
 convergence, stronger large-scale ascent, vertically coupled circulation structures, and increased convective instability.
 These combined dynamical and thermodynamic conditions provide a favourable environment for the initiation and
 organization of MCSs.

3.3 Distinct environmental controls of S-GX and PRD MCS

As shown in the previous sections, post-flood-season MCSs activity over SC is primarily concentrated in the PRD and S-GX
 regions (Fig. 2). To explain the regional difference governing the MCSs occurrence over the two regions, a dividing line at
 111.2°E separates the study area into these two subregions. Therefore, the MCS events are classified into two categories
 260 according to their initiation regions: (1) MCSs initiated over S-GX, hereafter referred to as “S-GX MCS”, and (2) MCSs
 initiated over the PRD, hereafter referred to as “PRD MCS”.

3.3.1 Dynamical environments

Both MCS types occur under the combined influence of the South Asian High (SAH), the western North Pacific subtropical
 high (WNPSH), and southerly moisture transport. However, their circulation configurations exhibit notable differences. For
 265 S-GX MCS events (Fig. 6a), the SAH extends farther eastward, while the WNPSH exhibits a relatively westward position,
 producing stronger southerly flow toward southern Guangxi (Fig. 7 a, g). The vertically integrated water vapor flux shows a
 clear transport pathway from the Bay of Bengal and northern South China Sea toward S-GX. Moreover, the strong low-level
 southwesterly flow (925 hPa) weakens as it approaches the coastal region of Guangxi, enhancing low-level convergence
 through flow deceleration and terrain interaction (Fig. 7b, h), which favours convection initiation over southern Guangxi
 270 (Huang et al., 2022). In contrast, PRD MCSs occur under a relatively eastward-retreated WNPSH configuration (Fig. 6b).
 Moisture transport is weaker and more broadly distributed over the northern South China Sea and coastal Guangdong.
 Consequently, upward motion is mainly confined to the PRD region, where localized low-level convergence develops as the
 weaker background flow decelerates near the coastal terrain (Fig. 7b, e). Notably, the low-level wind speed associated with
 PRD MCSs is considerably weaker than that associated with S-GX MCSs, suggesting that convection initiation in the PRD
 275 may be more strongly influenced by local boundary-layer processes under weaker synoptic forcing.

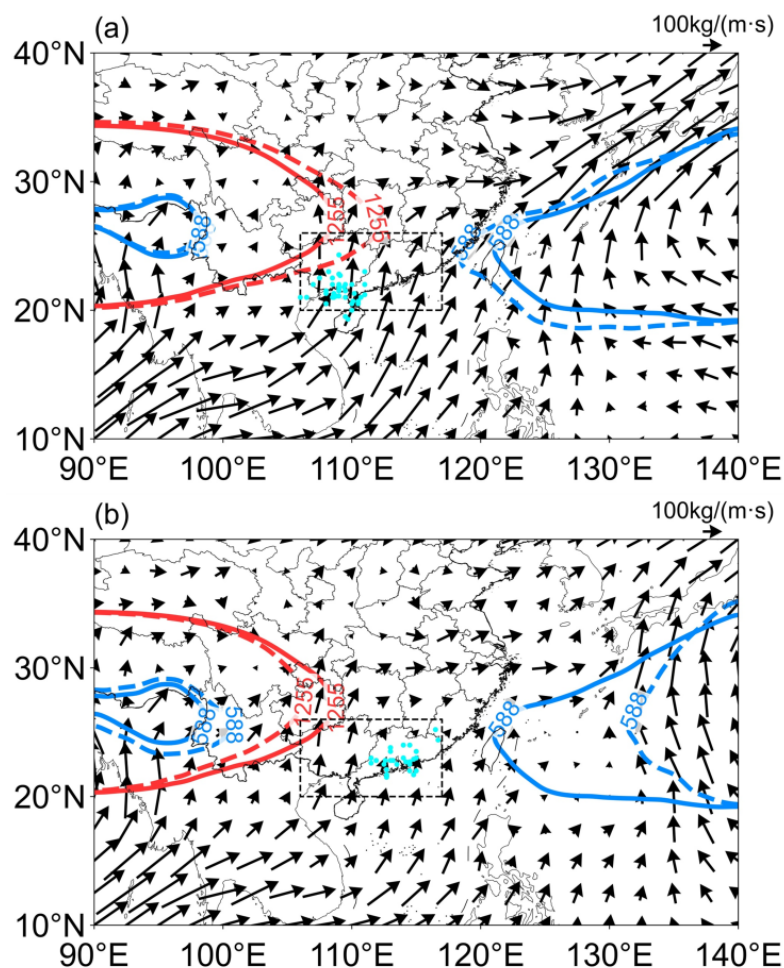


Figure 6. (a) Composite circulation patterns for all MCS days (solid contours) and S-GX MCS days (dashed contours). Red contours denote the South Asian High (SAH; 1250 gpm), and blue contours indicate the Western North Pacific subtropical high (WNPSH; 5880 gpm). Black arrows represent the composite vertically integrated water vapor fluxes ($100 \text{ kg m}^{-1} \text{ s}^{-1}$) during S-GX MCS days. Cyan dots denote MCS formation locations. The dashed rectangle marks the analysis region (106–117°E, 20–26°N). (b) Same as (a), but for PRD MCS days (dashed lines).

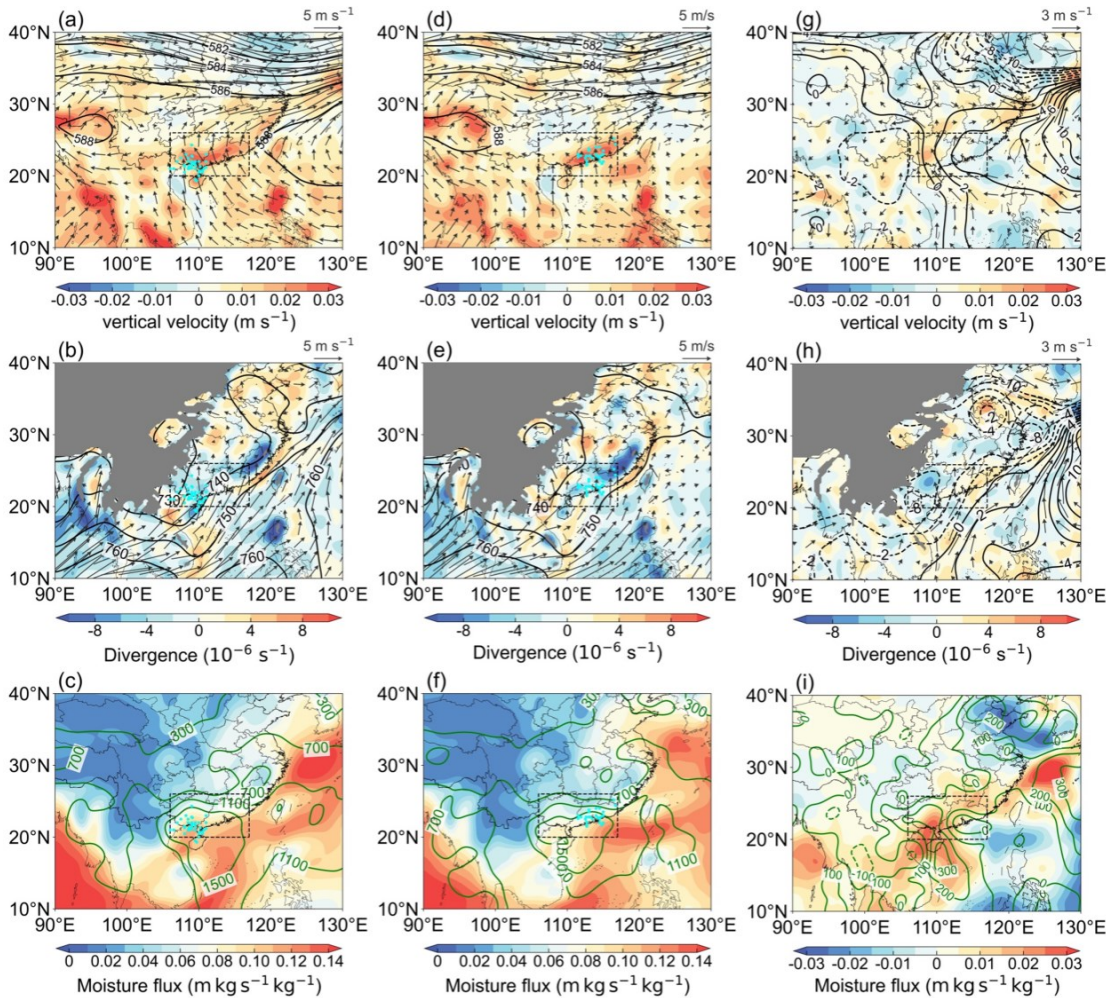


Figure 7. (a–c) Composite environmental conditions for S-GX MCSs days. (d–f) Same as (a–c), but PRD MCSs days; (g–i) Differences between S-GX and PRD MCS days (S-GX minus PRD). (a, d, g) 500 hPa geopotential height (contours; m) and horizontal winds (vectors), with shading indicating vertical velocity (m s^{-1}). (b, e, h) 925 hPa geopotential height (contours; m) and horizontal winds (vectors), with shading indicating horizontal divergence (10^{-6} s^{-1}). (c, f, i) Convective available potential energy (CAPE; contours; J kg^{-1}) and 925-hPa horizontal moisture flux (shading; $\text{kg m}^{-1} \text{ s}^{-1}$). Blue dots denote MCS formation locations. Gray lines indicate provincial boundaries and coastlines. Dashed boxes mark the analysis region ($106\text{--}117^\circ\text{E}$, $20\text{--}26^\circ\text{N}$).

The stronger dynamical forcing associated with S-GX MCSs is also evident in their vertical structures (Fig. 8). Compared with PRD MCSs days, the S-GX MCSs days on S-GX region days are featured with stronger low-level convergence, particularly below 900 hPa, together with deeper ascending motion extending through the troposphere. This vertically coupled circulation structure suggests that S-GX MCSs are more strongly supported by organized large-scale dynamical forcing. Quantitative comparisons further confirm these differences (Fig. 9a, b), with S-GX MCSs exhibiting stronger mid-level ascent (mean 500 hPa $\omega \approx -0.081 \text{ Pa s}^{-1}$) and larger vertical wind shear ($\approx 5.15 \text{ m s}^{-1}$) than PRD MCSs. These dynamical characteristics provide a more favourable environment for the organization and maintenance of deep convection.

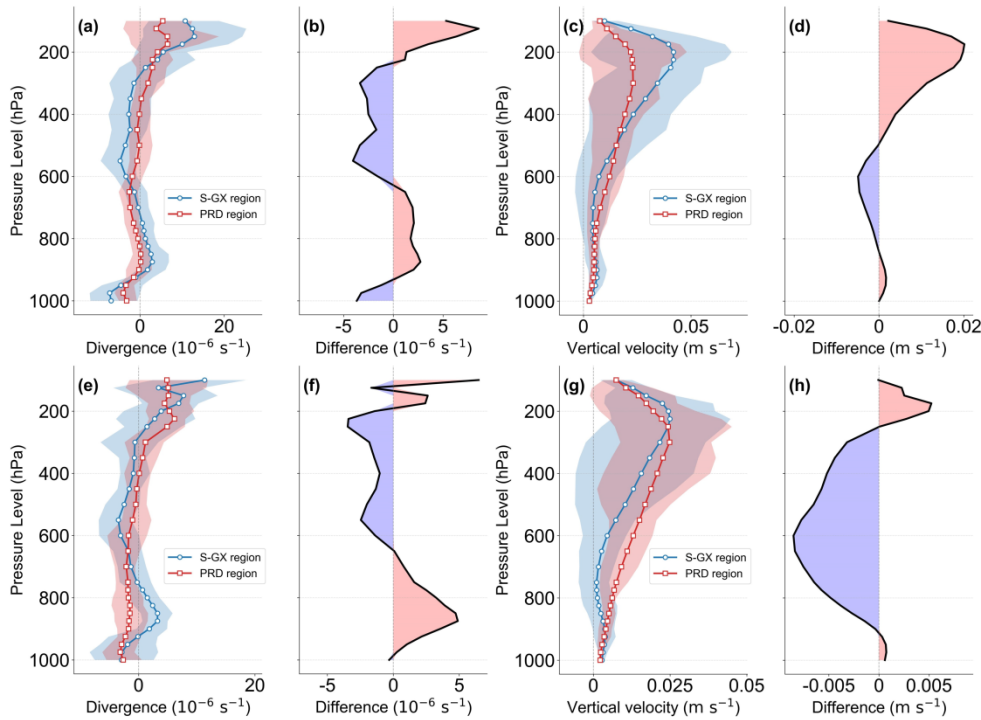


Figure 8. (a–d) Vertical profile of horizontal divergence (a–b) and vertical velocity (c–d) associated with the S-GX MCS days. (a) Divergence (10^{-6} s^{-1}) and (c) vertical velocity (m s^{-1}) for S-GX MCS days over the S-GX region (blue) and the PRD region (red), respectively. Solid lines represent the mean vertical profiles, and the shaded areas denote the interquartile range. (b) Divergence and (d) vertical velocity differences between the two regions (S-GX region minus PRD region). The divergence and vertical velocity profiles are calculated over the red outlined region shown in Fig. 2c. (e–h) Same as (a–d), but for the PRD MCS days.

3.3.2 Thermodynamic environments

The two MCS types also exhibit distinct thermodynamic characteristics (Figs. 7c, f and 9c, d). S-GX MCSs occur in an environment characterized by strong moisture transport and relatively high convective instability over S-GX, with mean CAPE reaching approximately 1843 J kg^{-1} (Fig. 9c). Notably, CAPE over S-GX is generally higher than that over the PRD regardless of MCS occurrence, but this contrast becomes more pronounced during S-GX MCS days. Meanwhile, S-GX is also characterized by relatively larger CIN ($70\text{--}220 \text{ J kg}^{-1}$) than the PRD ($70\text{--}140 \text{ J kg}^{-1}$), indicating a stronger convective inhibition barrier. However, CIN decreases during S-GX MCS days compared with non-MCS conditions, suggesting that enhanced dynamical forcing is required to overcome the inhibition and initiate convection (Fig. 9d).

In contrast, PRD MCSs develop under weaker large-scale dynamical forcing but within an environment with relatively weaker convective inhibition. Although CAPE is lower than that over S-GX (approximately 1523 J kg^{-1}), the smaller CIN over the PRD indicates that convection can be initiated under weaker lifting conditions. Combined with the afternoon peak of PRD MCS formation (Fig. 3), these characteristics suggest that PRD MCSs are more strongly influenced by local thermodynamic processes, including daytime boundary-layer heating and mesoscale thermal circulations. Combined with the



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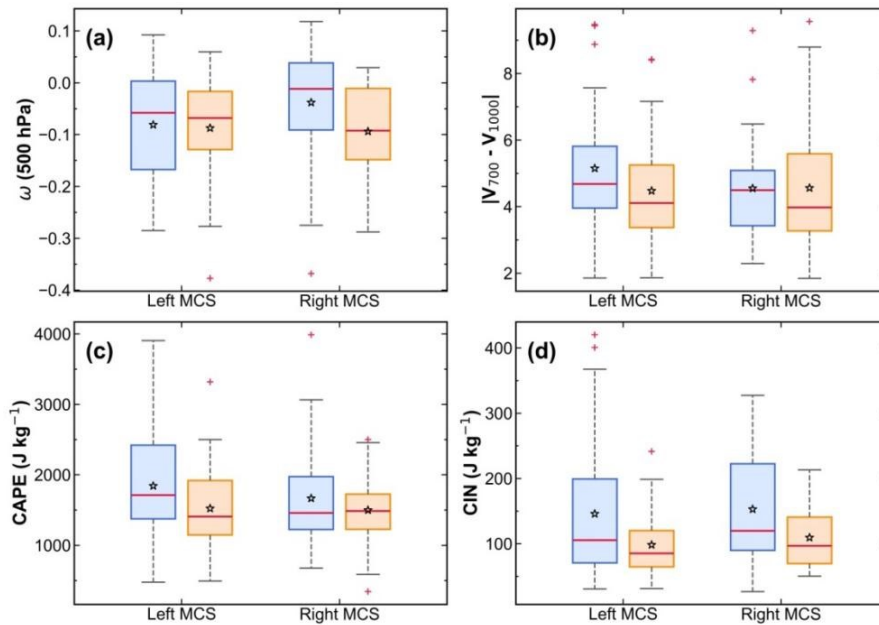


Figure 9. Boxplot comparison of regional-mean dynamical and thermodynamic parameters over the two analysis subregions during S-GX MCS days and PRD MCS days in South China. (a) 500 hPa vertical velocity (ω ; Pa s^{-1}), (b) the vertical wind shear between surface and 700 hPa (VWS; m s^{-1}), (c) convective available potential energy (CAPE; J kg^{-1}), and (d) convective inhibition (CIN; J kg^{-1}). The parameters are averaged over the two analysis subregions. Blue and orange boxplots respectively represent the S-GX and PRD analysis subregions. Boxes indicate the interquartile range (25th–75th percentiles), with the median shown by the horizontal red line. Whiskers denote the range excluding outliers, stars indicate mean values, and red crosses represent outliers.

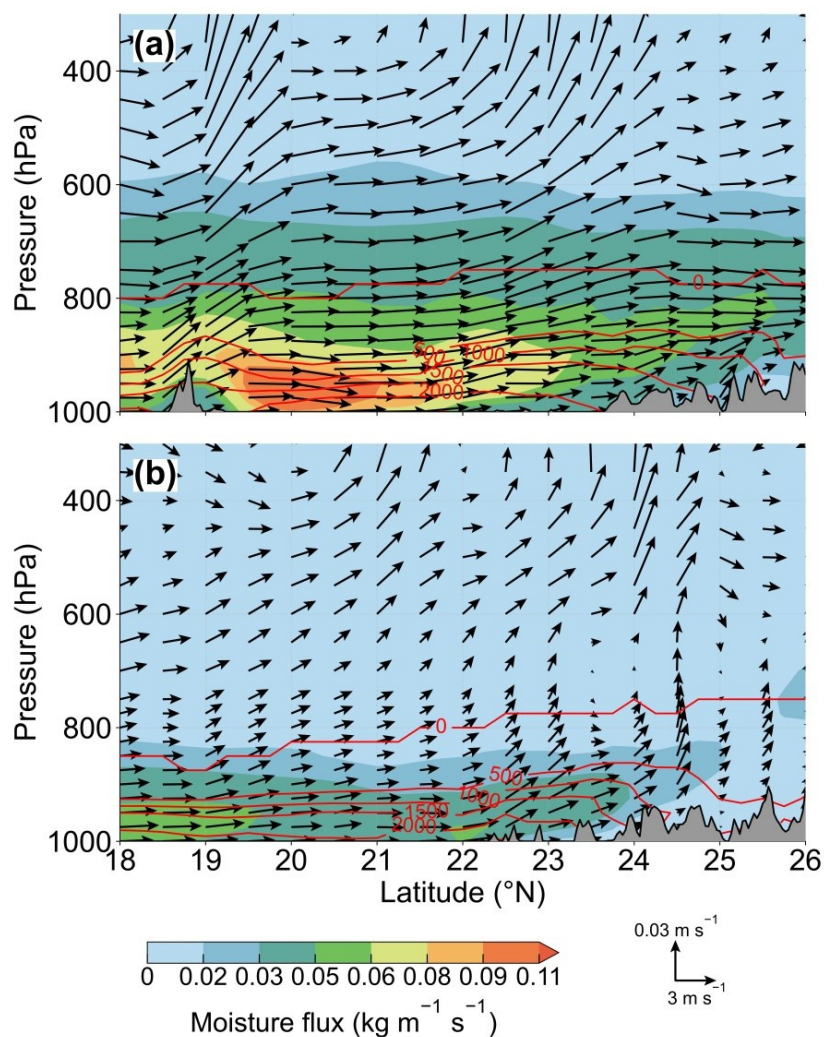
3.3.3 Vertical moisture – convection coupling

The vertical distribution of moisture transport further reveals the contrasting development mechanisms of the two MCS types (Fig. 10). For S-GX MCSs, moisture flux exceeding $0.04 \text{ kg m}^{-1} \text{ s}^{-1}$ extends from near the surface to approximately 750 hPa, indicating a relatively deep layer of strong southerly flow transporting abundant moisture from the Beibu Gulf and northern South China Sea toward S-GX. Winds between the surface and 700 hPa reach approximately 4.9 m s^{-1} . This deep moist inflow, together with low-level convergence and terrain-enhanced lifting, provides sufficient dynamical forcing to help overcome the relatively large CIN over S-GX and initiate deep convection.

In contrast, moisture transport associated with PRD MCSs is weaker and shallower. Moisture flux exceeding $0.04 \text{ kg m}^{-1} \text{ s}^{-1}$ is largely confined below approximately 900 hPa over the coastal PRD, while winds between 900 and 700 hPa are approximately 2.8 m s^{-1} , relatively weaker than those associated with S-GX MCSs. Near-surface winds below 900 hPa reach approximately 4.1 m s^{-1} and may be comparable to those during S-GX MCS events, suggesting that the principal difference lies in the vertical depth rather than solely in the near-surface strength of the moist inflow. The shallower moisture transport,



weaker mid-level ascent, and more localized convergence indicate that PRD MCS initiation depends less on persistent, deep monsoonal forcing and more on processes confined to the lower troposphere.



340 **Figure 10.** (a) Vertical cross sections along 109°E during S-GX MCS days. (b) Same as (a), but along 114.2°E during PRD MCS days. Shading indicates horizontal moisture flux ($\text{kg m}^{-1} \text{s}^{-1}$), arrows indicate horizontal and vertical wind vectors, and red contours indicate convective available potential energy (CAPE; J kg^{-1}).

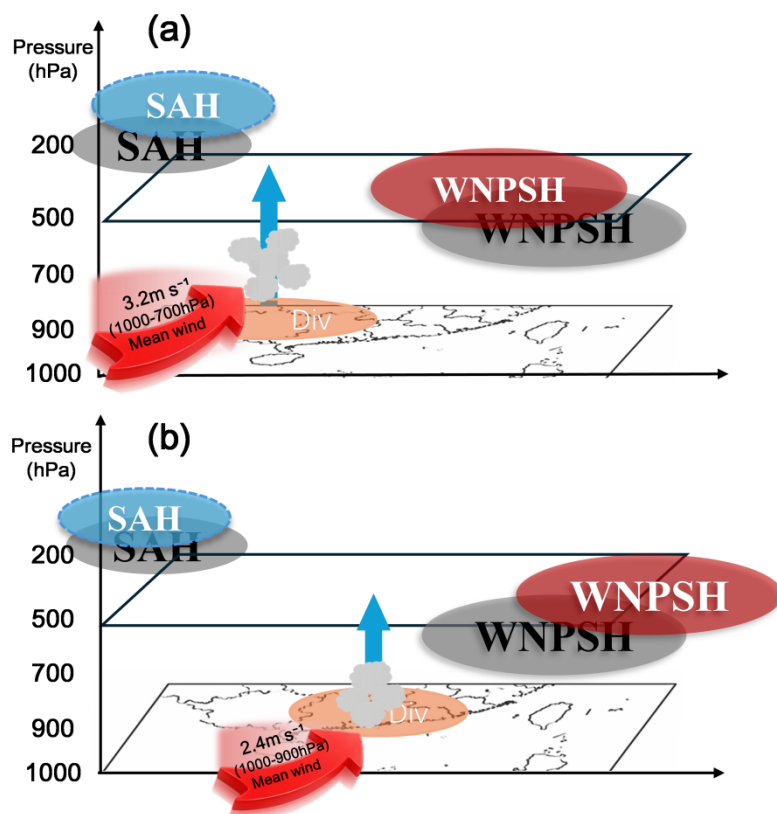


Figure 11. Conceptual illustrations of the environmental controls associated with (a) MCSs over southern Guangxi (S-GX) and (b) MCSs over the Pearl River Delta (PRD) during the post-flood rainy season over South China. Blue and brown ellipses indicate the characteristic positions of the South Asian High (SAH) and Western North Pacific subtropical high (WNPSH) associated with the formation of the S-GX MCS and PRD MCS, respectively, while grey ellipses denote their mean positions during all MCS events. Orange regions denote the preferred MCS occurrence areas. Blue arrows indicate upward motion, red arrows represent the mean low-level wind along the cross section (shown in Fig. 2c), with the annotated values indicating the layer-averaged wind speed (1000–700 hPa for S-GX MCSs and 1000–900 hPa for PRD MCSs), and “Div” denotes lower-level divergence associated with MCS development.

4. Summary and conclusions

Based on multi-source observational data, this study investigated the spatiotemporal characteristics and environmental conditions of non-tropical-cyclone (non-TC) mesoscale convective systems (MCSs) during the post-flood rainy season (July–September) over South China (SC). The major findings are summarized as follows.

(1) Non-TC MCSs exhibit pronounced spatial and temporal heterogeneity during the post-flood rainy season. MCS activity is primarily concentrated over southern Guangxi (S-GX) and the Pearl River Delta (PRD), with formation occurring preferentially along the coastal regions. Their diurnal evolution also differs substantially between the two regions. MCSs over the PRD generally initiate from late night to morning and organize during the afternoon, whereas those over S-GX



preferentially initiate from midnight to early morning and develop throughout the morning and daytime. These results suggest that post-flood-season MCSs are characterized by distinct regional development pathways.

(2) Non-TC MCSs occurrence is associated with a vertically coupled dynamical and thermodynamic environment. Compared with non-MCS days, MCS days exhibit enhanced low-level moisture transport and convergence, stronger mid-tropospheric ascent, upper-level divergence, and increased convective instability. The combined effects of moisture supply, dynamical lifting, and atmospheric instability provide a favorable environment for the initiation, organization, and maintenance of MCSs during the post-flood rainy season.

(3) Two distinct environmental modes of post-flood-season MCS development are identified (Fig. 11). The relative configuration of the South Asian High (SAH) and the western North Pacific subtropical high (WNPSH) determines different circulation regimes and moisture transport pathways for S-GX and PRD MCSs. S-GX MCSs over S-GX occur under an eastward-extended SAH and a westward-displaced WNPSH, which enhance southwesterly monsoonal flow and establish a deeper moisture transport layer extending from the surface to approximately 750 hPa. Together with larger convective instability (mean CAPE $\approx 1843 \text{ J kg}^{-1}$), allowing convection to overcome the relatively larger CIN and organize into MCSs. PRD MCSs over the PRD develop under a relatively eastward-retreated WNPSH and weaker large-scale forcing, with shallower moisture transport confined mainly below 900 hPa, smaller CIN, and lower but more localized instability (mean CAPE $\approx 1523 \text{ J kg}^{-1}$), making convection more dependent on boundary-layer processes such as daytime heating and sea-breeze convergence.

This study advances the understanding of post-flood rainy season non-TC MCSs over SC by identifying their distinct spatiotemporal characteristics and environmental controls. In particular, the proposed synoptic–dynamical and boundary-layer thermodynamic development modes provide a physically based framework for interpreting regional differences in MCS initiation and organization. These findings have important implications for improving conceptual models of warm-season convection, convection-permitting numerical simulations, and operational forecasting of short-duration heavy rainfall over SC. Although this framework is supported by multi-source observations, its robustness across different climate backgrounds and longer time periods remains to be further evaluated. Future studies combining extended observational records with convection-permitting simulations will help refine this framework.

Code and data availability

The radar composite reflectivity mosaics used in this study can be obtained by contacting the corresponding author. The tropical cyclone best-track dataset is publicly available from the China Meteorological Administration Tropical Cyclone Data Center (<https://tcdata.typhoon.org.cn/zjljsjj.html>), and the ERA5 reanalysis data are available from the Copernicus Climate Change Service Climate Data Store (<https://cds.climate.copernicus.eu/>). The data in this study were analysed using Python (Python Software Foundation; <https://www.python.org/>). All relevant codes used in this study and the processed MCS dataset preserves the key variables required for the analyses are available, upon request, from the corresponding author.



Author contributions

W.J. conducted the data processing, formal analysis, investigation, visualization, and preparation of the original manuscript. Y. C. conceptualized the study, developed the methodology, supervised the research, and contributed to manuscript review and editing. J.F.Z. provided resources and methodological guidance and contributed to manuscript revision. C.W. contributed to data curation and validation. Y.G. contributed to formal analysis and validation. J.T.L. assisted with data processing and figure preparation. J.Z. contributed to data curation and validation. All authors contributed to the review and editing of the manuscript and approved the final version.

Competing interests

The authors declare that none of the authors has any competing interests.

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