

Characteristics of Warm-Season Mesoscale Convective Systems with Different Movement Paths Generated over the Tibetan Plateau and Their Subseasonal Variations

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ABSTRACT: Mesoscale convective systems (MCSs) over the Tibetan Plateau (TP) can significantly impact local environments and further affect surrounding regions when moving out of the TP. However, the characteristics of MCSs with different movement paths and their subseasonal variations remain unclear. Based on half-hourly GPM satellite data from 23 warm seasons (2001–23), this study reveals that the dominant movement paths of MCSs generated over TP are the southeast (SE), northeast (NE), and southwest (SW) paths, accounting for approximately 50%, 30%, and 15% of the total MCSs, respectively. For MCSs dissipating locally (LT-MCSs), eastward-moving MCSs travel faster and exhibit stronger maximum precipitation, while for moving-out MCSs (MT-MCSs), the SW path exhibits the highest strengths in terms of various properties. MCSs generated over the southern (eastern) part of TP tend to move out of TP along the south (east) path, while those in the center TP quickly dissipate. Notably, maximum precipitation increases with the distance away from the TP for MT-MCSs with the SE and SW paths but decreases for the NE path. Regarding subseasonal variations, the occurrences of both MT-MCSs and LT-MCSs increase from May to July and then decrease, and the ratio of MT-MCSs to total MCSs during midsummer (i.e., July and August) is lower than that during other months. Meanwhile, the number of eastward-moving MT-MCSs decreases during midsummer, accompanied by the westward shift of the high value centers of maximum precipitation, which can be attributed to the subseasonal variations of circulation and water vapor transport.

KEYWORDS: Tibetan Plateau; Cloud tracking/cloud motion winds; Convective storms/systems; Mesoscale systems; Summer/warm season; Subseasonal variability

1. Introduction

The Tibetan Plateau (TP), with an average elevation of over 4000 m, is the largest cryosphere outside the polar regions and is often referred to as the “Third Pole” (Yao et al. 2022; Jiang et al. 2023). It is well known that the TP plays a crucial role in shaping the monsoon climate in East Asia and influencing global climate patterns (Zhou et al. 2009; Wu et al. 2015; Huang et al. 2023). Furthermore, as the source of many of Asia’s major rivers, the TP is a vital ecological barrier that ensures the stability of the climate system, provides water resources, protects biodiversity, and helps balance the carbon budget across East and South Asia (Liu et al. 2020; X. Li et al. 2022; Yao et al. 2022).

In summer, due to the thermal effects of the topography, the TP manifests as a stable and strong anticyclone in the upper troposphere, while a robust cyclone forms near the surface in the midtroposphere, which favors the frequent occurrence of convective events (Sugimoto and Ueno 2010; Wu et al. 2015; Fu et al. 2020; Cao et al. 2024). Convective systems on the TP contribute 30%–70% of the total summer precipitation, with more than 90% of this precipitation being generated by deep convections (Hu et al. 2017; Fu et al. 2019; Kukulies et al. 2019; Na et al. 2024). Under favorable atmospheric conditions, these deep convections organize into larger-scale

mesoscale convective systems (MCSs) which have significant impacts on both the TP and surrounding regions (Li et al. 2008; Rasmussen and Houze 2012; Kukulies et al. 2023).

Previous studies have shown that MCSs can form anywhere on the TP, with their precipitation contributing approximately 10%–40% of the total precipitation in the TP (Feng et al. 2021b; Kukulies et al. 2021). The majority of MCSs remain locally confined within the TP, yet they exert substantial influence on regional ecology and hydrological cycle (Mai et al. 2021; Yao et al. 2022; Xu et al. 2024). Under certain atmospheric conditions, a small proportion of MCSs persist longer, propagate outside the TP, and produce more extreme or excessive precipitation (Hu et al. 2016; Fu et al. 2021; Kukulies et al. 2023). It is widely recognized that some of the most intense rainstorms, severe flooding, and urban waterlogging events can be attributed to moving-out MCSs (Li et al. 2008; Rasmussen and Houze 2012; Wang et al. 2019; Zhao et al. 2019; Chen et al. 2020). Therefore, whether MCSs dissipate locally or move out of the TP has profound implications for regional climate and hydrological extremes. Some studies have categorized MCS movement paths based on the influencing circulation systems, classifying them as either eastward or westward moving (Tang et al. 2020; Kukulies et al. 2021; Yao et al. 2022; Zhang et al. 2024). Others have classified MCSs into eastward-moving and non-eastward-moving types based on whether they propagate downstream (Medina et al. 2010; Fu et al. 2021; Mai et al. 2021). Despite differences in categorization methods, the results all indicated that the count of

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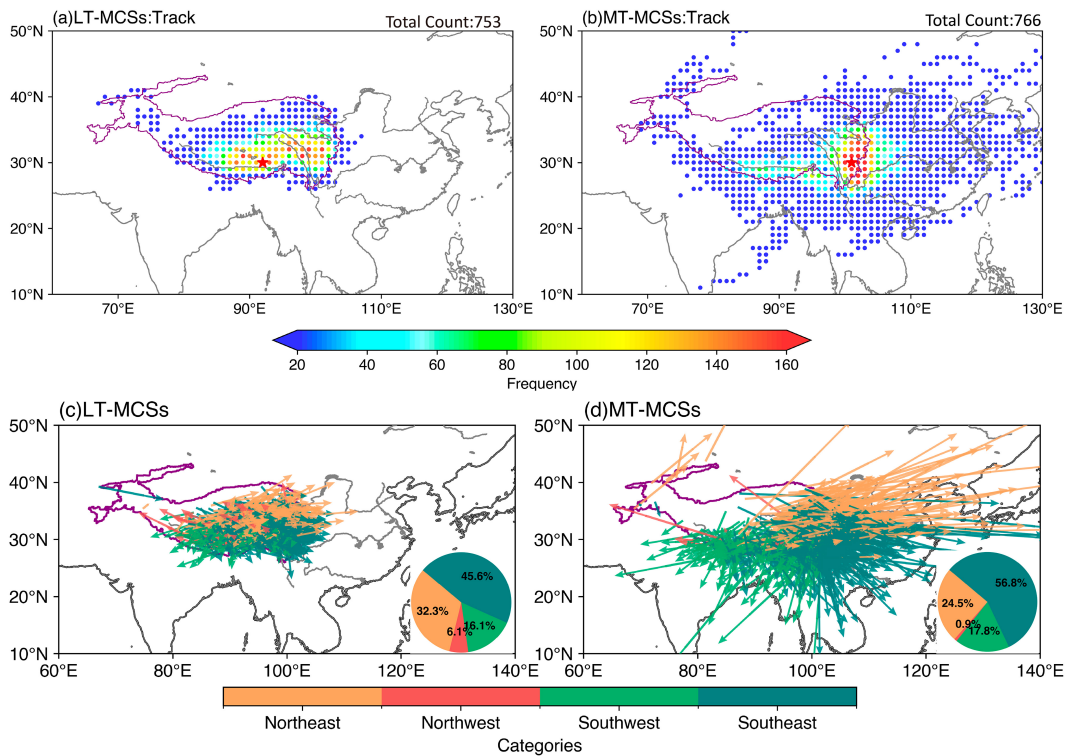


FIG. 1. Spatial distribution of (a),(b) occurrence frequencies and (c),(d) movement trajectories of (a),(c) LT-MCSs and (b),(d) MT-MCSs generated over the TP during the warm season (May–September) from 2001 to 2023. In (a) and (b), the number in the top-right corner is the total count of MCSs, and the red star with number denotes the maximum value of the frequency. In (c) and (d), the numbers within pie charts denote the fraction of different movement paths. The purple line denotes the boundary of the TP above 3000 m.

different types of MCSs peak in the summer (Hu et al. 2016; Kukulies et al. 2021; Mai et al. 2021).

As documented in previous studies (Mai et al. 2021; Kukulies et al. 2021, 2023), deep convection over the TP is often influenced by the synoptic circulation. Specifically, the South Asian high (SAH), the subtropical westerly jet, and the Tibetan systems (shear, vortex, troughs) together create favorable dynamic conditions for the development of convection (Hu et al. 2016; Kukulies et al. 2021; S. Liu et al. 2024; Zhang et al. 2025). It also has been widely accepted that most of water vapor in the TP is provided by the westerly and monsoon circulation systems (You et al. 2021; Yao et al. 2022; Zhang et al. 2024). In addition, the strong spatial heterogeneity of water vapor makes the eastern and southern parts of the TP more conducive to MCS development (Tang et al. 2020; Zhao and Zhou 2020; Y. Li et al. 2022). Moreover, the MCSs in the eastern TP are more likely to interact with downstream circulation systems, which helps them redevelop and propagate after moving out of the TP (Fu et al. 2019, 2020; Mai et al. 2021; Ma et al. 2023).

Significant scientific advances in recent years have been made regarding MCSs over the TP and their movement paths (Hu et al. 2016; Wang et al. 2019; Fu et al. 2021; Kukulies et al. 2021; Mai et al. 2021). However, quantitative understandings of the precipitation features, moving speed, lifetime, and other important characteristics of MCSs with different movement

paths are still limited. Meanwhile, the subseasonal variations of MCSs with different movement paths and their associated features remain unclear. This study aims to investigate the characteristics of MCSs over the TP by using a modern tracking method (Feng et al. 2021b, 2023) to analyze satellite data during the warm seasons (May–September) spanning 2001–23. The rest of the paper is organized as follows. Section 2 describes the satellite data and tracking algorithm used in this study. Section 3 presents the spatial and subseasonal variations of MCS with different movement paths and associated precipitation features, lifetime, circulation backgrounds, and so on. Section 4 concludes the main findings with a discussion about future studies.

2. Data and methods

a. Observational and reanalysis datasets

The NASA global merged IR V1 infrared brightness temperature (T_b) dataset is a merged geostationary satellite dataset, covering from 60°S to 60°N globally with a horizontal resolution of about 4 km and a temporal resolution of 30 min (Janowiak et al. 2017). The 0.1° × 0.1° and 30-min interval Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) V06 B precipitation dataset is based on passive microwave sensors and infrared

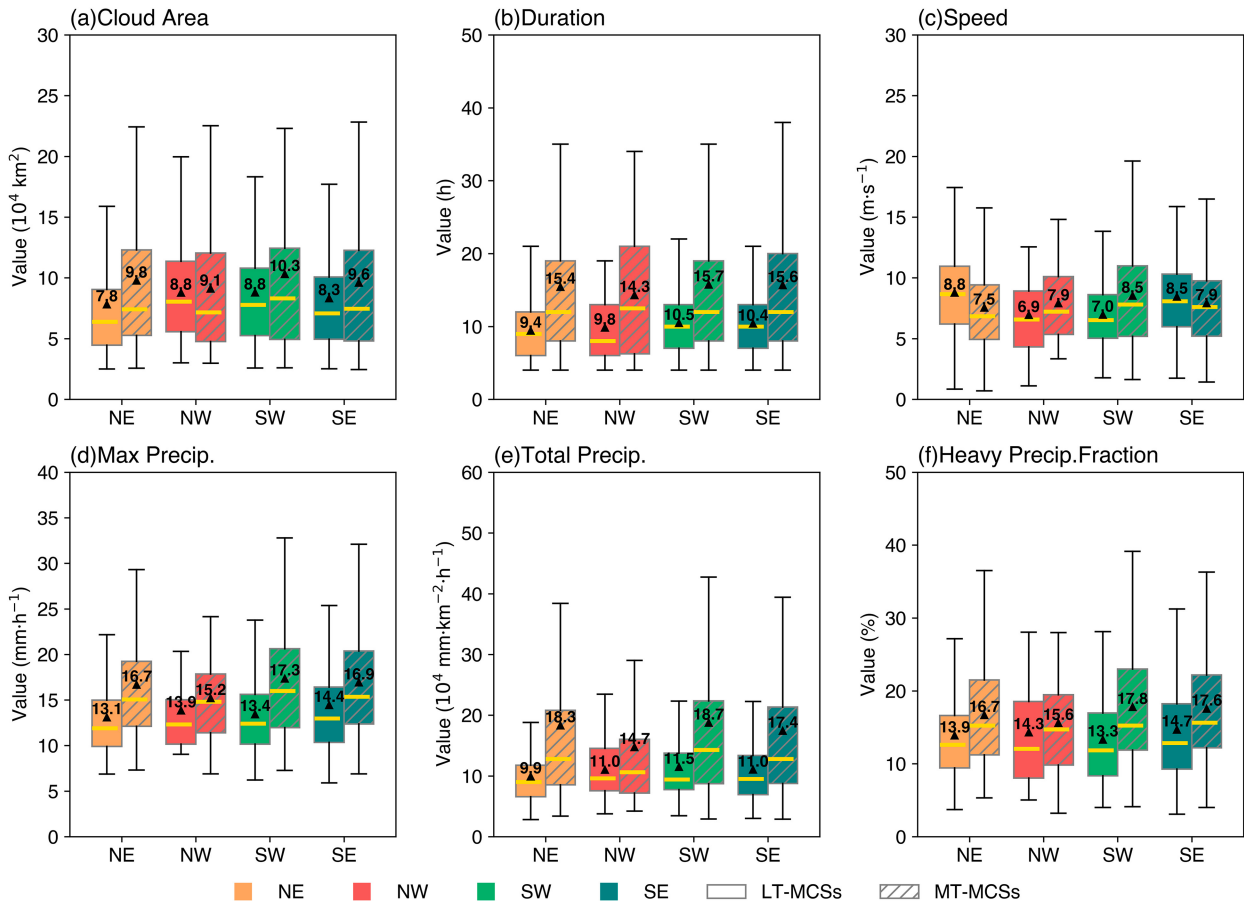


FIG. 2. Box-and-whisker plots of (a) cloud area (10^4 km^2), (b) duration (h), (c) moving speed (m s^{-1}), (d) maximum precipitation (mm h^{-1}), (e) total precipitation ($10^4 \text{ mm km}^{-2} \text{ h}^{-1}$), and (f) fraction of heavy precipitation to total precipitation (%) for LT-MCSs and MT-MCSs with different movement paths. In each box, the horizontal bar denotes the median values, the black triangle and number represent the mean values, the boundaries of the colored area indicate the interquartile range (25th and 75th percentiles), and the upper and lower whiskers are the 25th/75th percentiles $\pm 1.5 \times (75\text{th percentiles} - 25\text{th percentiles})$.

geostationary satellite rainfall retrievals (Huffman et al. 2023). Previous evaluation studies over the world suggested that the MCS tracking results by using GPM_MERGIR Tb and GPM_IMERG precipitation product provide consistent results (Feng et al. 2021a; Kukulies et al. 2021; Huffman et al. 2023; Dai et al. 2024; Wang et al. 2024; Lu et al. 2025). To align with the time interval and grid spacing, the global Tb dataset is resampled to $0.1^\circ \times 0.1^\circ$ spatial resolution. Moreover, to make the MCSs tracking results easier to interpret, the hourly Tb data at 0000 UTC are used to represent convective clouds for that hour. Hourly precipitation data are calculated as the average of the data recorded at 0000 and 0030 UTC of the hour, with the unit being millimeters per hour (Feng et al. 2021b, 2023). The integrated data of Tb and precipitation for observational MCS identification encompass the study area ($0^\circ\text{--}50^\circ\text{N}$, $60^\circ\text{--}130^\circ\text{E}$), with the Tibetan Plateau region being defined as the area with an elevation exceeding 3000 m, outlined by the purple line (Fig. 1).

The ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate and was developed through the Copernicus Climate Change Service (C3S) (Hersbach et al. 2020). The atmospheric variables we used in this paper are the

geopotential height, horizontal wind fields, vertical velocity, the vertical integration of eastward (northward) water vapor flux, and their divergence at both surface and pressure levels. The time lengths of all the selected datasets cover the period of 2001–23, and warm seasons refers to May–September. Specifically, we employ the average of hourly high-resolution realization (around 31 km) data at 0000, 0600, 1200, and 1800 UTC composited daily data to describe the large-scale atmospheric circulation. In addition, the hourly variables such as vorticity, horizontal and vertical velocity at 500 hPa, convective available potential energy (CAPE), and 10-m horizontal winds are used to investigate the variations of dynamic and thermodynamic conditions governing the initiation and propagation of MCSs.

b. MCS tracking method and criteria

We employ the Flexible Object Tracker (FLEXTRKR) tracking algorithm, which has been widely used for MCS tracking and has been proven to effectively reduce misidentifications of MCSs in high mountainous areas (Feng et al. 2021a; Dai et al. 2024; Prein et al. 2024; Wang et al. 2024). The algorithm

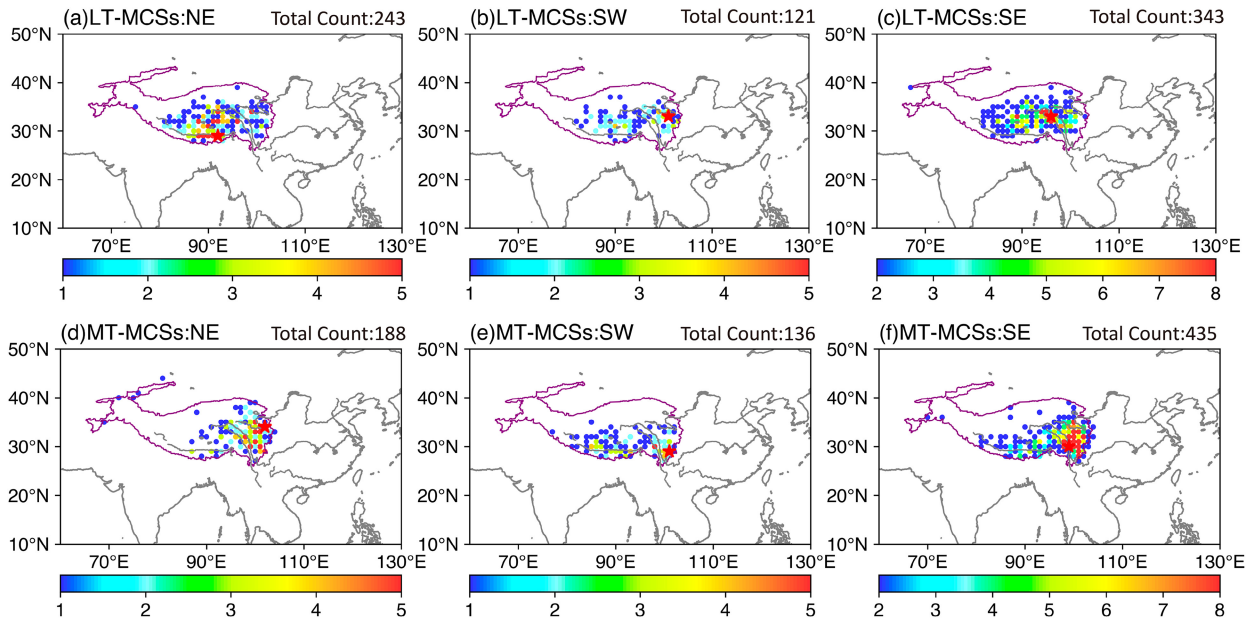


FIG. 3. The frequency distribution of generation of (a)–(c) LT-MCSs and (d)–(f) MT-MCSs with (a), (d) NE, (b), (e) SW, and (c), (f) SE movement paths. The red star, purple line, and total number in the top-right corner denote the maximum value, the TP, and the number of MCSs, respectively.

identifies cold cloud systems (CCSs) and precipitation features (PFs) based on brightness temperature and rain rate, respectively. CCSs are tracked when the overlap between two CCSs at consecutive time steps exceeds 50%. In this study, MCSs are defined as CCSs with a brightness temperature (T_b) < 221 K, which then iteratively expand to 241 K. Additionally, MCSs must have a horizontal area $> 40\,000$ km², a

mean PF rain rate > 2 mm h^{−1}, a heavy rain rate > 10 mm h^{−1}, skewness $> 5\%$, and a major axis length > 100 km for at least four continuous hours (Feng et al. 2019, 2021a).

The MCSs generated over the TP can be categorized into two types, which are 1) MCSs that move out of the TP, referred to as “moving-out type” (MT-MCSs), and 2) MCSs that remain within the TP and dissipate locally, referred to

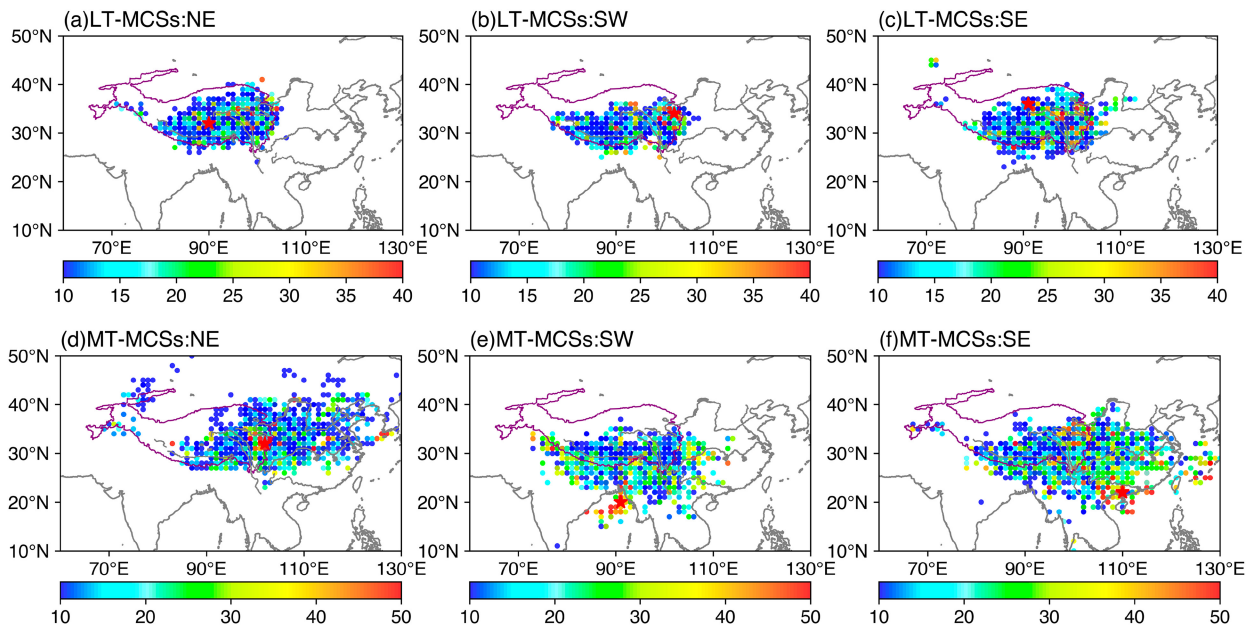


FIG. 4. As in Fig. 3, but for the distribution of the maximum precipitation (mm h^{−1}). The maximum precipitation is the mean of the hourly maximum precipitation at each time step of MCSs.

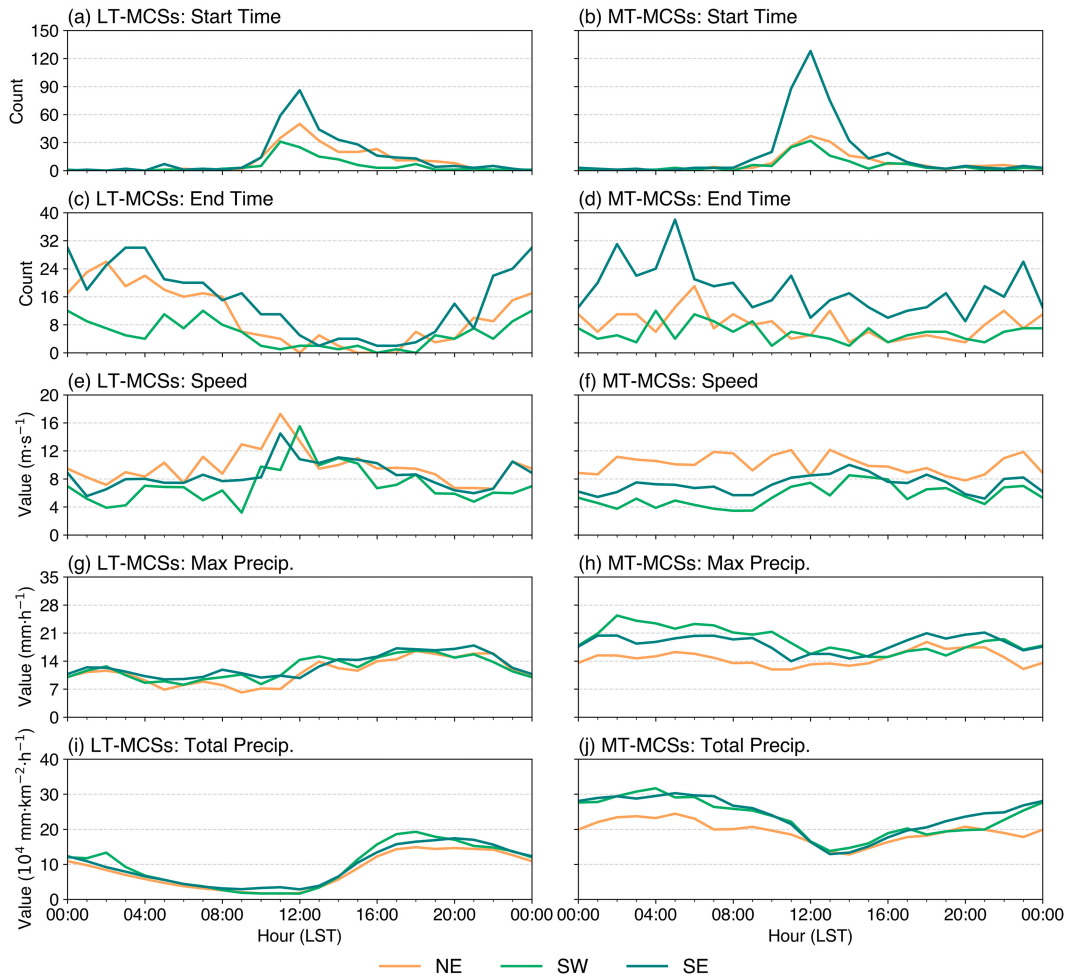


FIG. 5. The diurnal variations of (a),(b) start time, (c),(d) end time, (e),(f) moving speed (m s^{-1}), (g),(h) maximum precipitation (mm h^{-1}), and (i),(j) total precipitation ($10^4 \text{ mm km}^{-2} \text{ h}^{-1}$) for (a),(c),(e),(g),(i) LT-MCSs and (b),(d),(f),(h),(j) MT-MCSs among different movement paths. All times are in LST (i.e., UTC + 6 h).

as “local type” (LT-MCSs). Specifically, when more than half of MCS’s grids moved out of the TP, it is categorized as MT-MCSs. Using this approach, we identify 1519 MCSs generated over the TP, of which 753 are LT-MCSs and 766 are MT-MCSs. The movement path of an MCS is defined by the angle of the vector connecting its initiation and dissipation locations. Specifically, quadrants 1–4 correspond to northeast (NE), northwest (NW), southwest (SW), and southeast (SE) movement paths, respectively (Hu et al. 2016, 2017; Kukulies et al. 2021; Mai et al. 2021). For comparison, we also use colder Tb thresholds for CCS (cold core $\leq 200 \text{ K}$, extending to 261 K) and lower heavy rain rate (5 mm h^{-1}) defined by Kukulies et al. (2021). The results indicate that despite inconsistency in the total numbers of MCSs, the spatial distributions and the proportions of MCSs with different movement paths nearly remain unchanged (figure not shown).

The MCS algorithm provides not only trajectories of MCSs but also many statistical variables of MCSs and MCS-induced precipitation (Feng et al. 2021b, 2023). The variables used in this paper are duration, movement speed, cloud area,

total precipitation, total heavy precipitation ($\geq 10 \text{ mm h}^{-1}$), and maximum precipitation. Specifically, total precipitation is the sum of precipitation from all precipitation grids at each hour, the heavy precipitation fraction is the ratio of heavy precipitation to total precipitation, and maximum precipitation is the hourly maximum precipitation at each time step of MCSs. The movement speed of MCS between two adjacent times is computed as the relative displacement of precipitation field (intensity and pattern) divided by the time step based on a 2D cross-correlation approach. Please refer to Feng et al. (2023) for a more detailed description.

3. Results

a. Statistical characteristics of TP-MCSs with different movement paths

As documented in previous studies (Hu et al. 2016, 2017; Kukulies et al. 2021), LT-MCSs are most frequent in the central region of the TP, primarily within a zonal band between 30° and 35°N (Fig. 1a), while MT-MCSs are mostly occurring

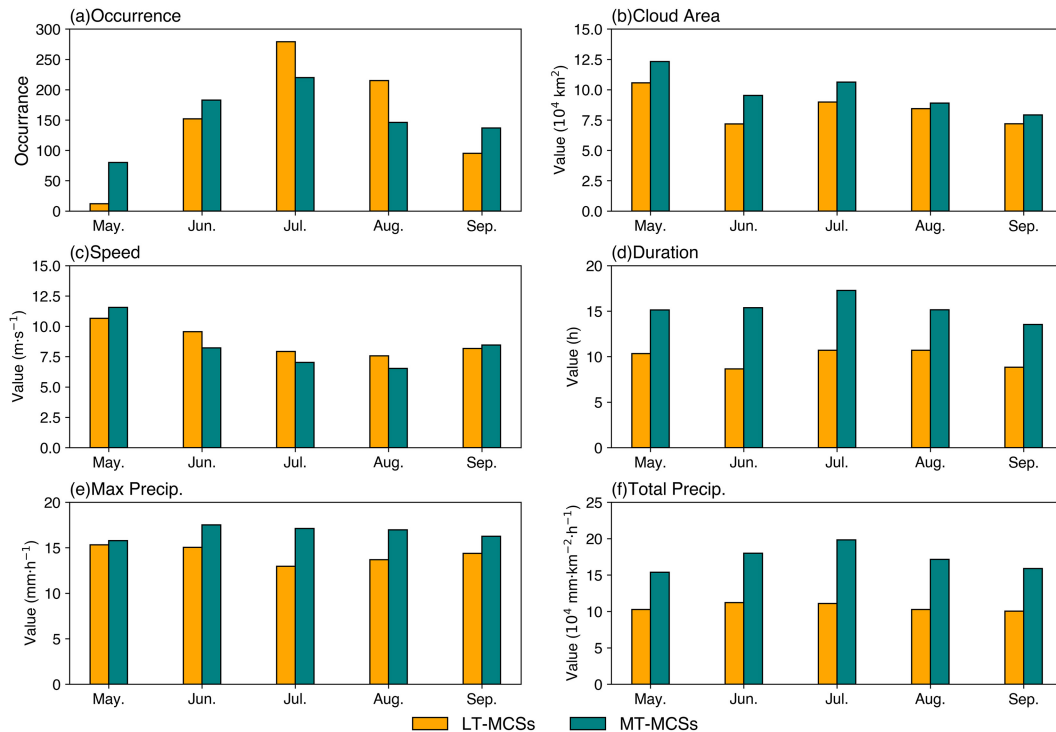


FIG. 6. The monthly mean values of (a) occurrences, (b) cloud area (10^4 km^2), (c) moving speed (m s^{-1}), (d) duration (h), (e) maximum precipitation (mm h^{-1}), and (f) total precipitation ($10^4 \text{ mm km}^{-2} \text{ h}^{-1}$) of LT-MCSs (yellow bars) and MT-MCSs (green bars).

along the eastern and southern edges of the TP (Fig. 1b). Furthermore, it is worth noting that in both LT-MCSs and MT-MCSs, the main paths are the SE, NE, and SW paths (Figs. 1c,d). Specifically, the SE path is accounting for about 57% in MT-MCSs and 46% in LT-MCSs. The NE path has the second highest frequency of occurrence, and the fraction is a bit larger for LT-MCSs than for MT-MCSs (32.3% vs 24.5%). In contrast, the NW paths are rarely observed, practically in MT-MCSs.

In Fig. 2, we present the statistical characteristics of several important MCS properties including cloud area, precipitation features, and so on. Compared to LT-MCSs, MT-MCSs generally exhibit larger cloud areas, longer durations, greater total precipitation, higher maximum precipitation, and higher proportion of heavy precipitation. Furthermore, the wider range of properties also indicates that the MT-MCSs have more extremity than LT-MCSs. For each type of MCS (i.e., LT-MCSs or MT-MCSs), remarkable differences exist among different movement paths. For LT-MCSs, eastward-moving MCSs (SE plus NE) travel faster and exhibit higher proportion of heavy precipitation but smaller cloud area and less total precipitation compared to westward-moving (NW plus SW) paths (Figs. 2a,c,e,f). Meanwhile, MCSs with the SW and SE paths have longer durations and stronger maximum precipitation than the NE path (Figs. 2b,d). For MT-MCSs, the SW path possesses higher values in terms of all properties compared to the other three movement paths. The rest paths show complicated characteristics. For instance, the NE path

has larger cloud area and higher total precipitation, but its duration, speed, and fraction of heavy precipitation are less than those of the SE path (Figs. 2a–f). In particular, the results show that the path dependence of maximum precipitation is consistent with that of heavy precipitation fractions (Figs. 2d,f).

Since more than 90% of MCSs move eastward or southward, in the following, we mainly focus on the spatial characteristics of MCSs with the NE, SE, and SW movement paths. The frequency distribution of MCS generation reveals significant differences among different paths (Fig. 3). For LT-MCSs, the locations of generation of MCSs with the NE and SE paths are concentrated in the central part of the TP (Figs. 3a,c), while that for the SW path has two centers, respectively, in the southwestern and southeastern part of the TP (Fig. 3b). For MT-MCSs, the high frequency of generation for the NE and SE paths are observed in the eastern part of the TP (Figs. 3d,f), while the frequency distribution for the SW path aligns with the LT-MCSs pattern (Fig. 3e). It can be concluded that MCSs generated in the central TP typically move toward the eastern TP and then dissipate. By contrast, MCSs generated over the south and east edges of the TP tend to move out along the southward and eastward paths, respectively, which are consistent with the findings of Kukulies et al. (2021) and Mai et al. (2021).

The spatial distributions of maximum precipitation are further analyzed for MCSs with different types and different movement paths (Fig. 4). For LT-MCSs, the distributions of maximum precipitation are generally path independent, and

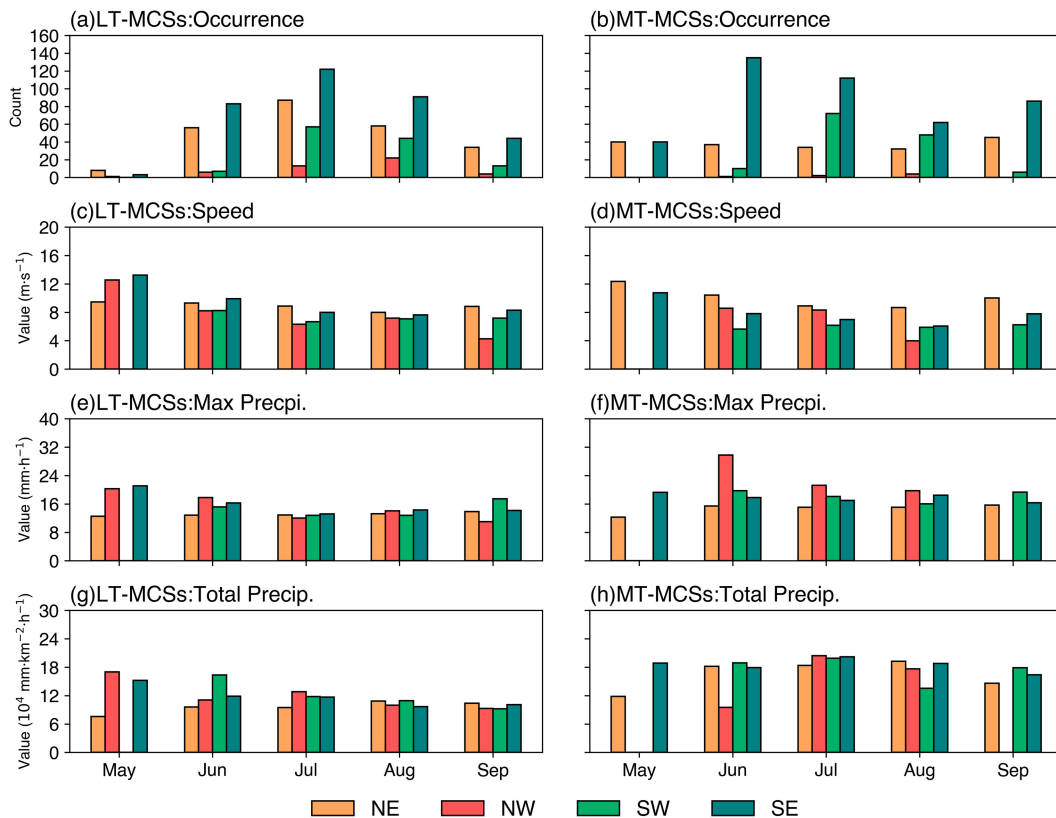


FIG. 7. The monthly mean values of (a),(b) occurrences, (c),(d) moving speed (m s^{-1}), (e),(f) maximum precipitation (mm h^{-1}), and (g),(h) total precipitation ($10^4 \text{ mm km}^{-2} \text{ h}^{-1}$) for (a),(c),(e),(g) LT-MCSs and (b),(d),(f),(h) MT-MCSs.

all paths exhibit relatively high precipitation intensity (greater than 30 mm h^{-1}) in the central and eastern parts of the TP. Compared to LT-MCSs, MT-MCSs have stronger precipitation intensity ($>50 \text{ mm h}^{-1}$) and exhibit notable differences across different movement paths (Figs. 4d–f). For the NE path, high values of maximum precipitation are located in the eastern part of the TP, implying that MCSs tend to become weak when moving out of the TP. Differently, high values of maximum precipitation for the SW and SE paths are located in the Bay of Bengal and southern China, respectively. This suggests that the MCS-induced precipitation gradually increases with the distance away from the TP (Figs. 4e,f) likely because the thermal conditions in the south is more favorable for the development of convection compared to over the TP.

Figure 5 presents the diurnal variations of several key properties (start time, end time, movement speed, maximum precipitation, and total precipitation) of LT-MCSs and MT-MCSs with different movement paths. Overall, both LT-MCSs and MT-MCSs typically initiate between 1000 and 1400 local solar time (LST) (Figs. 5a,b), consistent with the findings of Hu et al. (2010) and Lu et al. (2024). For LT-MCSs, all paths reach their highest movement speeds at around 1200 LST and peak rates of total and maximum precipitation at around 1800 LST (Figs. 5e,g,i). Then, they gradually dissipate during the nighttime (2000–0800 LST) (Fig. 5c). By contrast, MT-MCSs show

a less pronounced diurnal cycle except for total precipitation, which generally peaks between 0000 and 0600 LST (Fig. 5j).

b. Subseasonal variations of MCSs with different types and movement paths

Kukulies et al. (2021) pointed out that the total number of MCSs exhibits different subseasonal variations between the TP region and low elevation areas. Figure 6 demonstrates the subseasonal variations of some MCSs properties, which show that the occurrences, speed, and maximum precipitation are different between MT-MCSs and LT-MCSs (Figs. 6a,c,e). However, we also find that the cloud area, duration, and total precipitation have same intravariations in MT-MCSs and LT-MCSs (Figs. 6b,d,f). In particular, we observe that the occurring frequencies of both MT-MCS and LT-MCS increase from May to July and then decrease, but the occurrence of LT-MCSs is higher than MT-MCSs during midsummer (i.e., July and August) while lower in the other 3 months (Fig. 6a). Compared to the other 3 months, the movement speed is slower during midsummer, which might prevent MCSs from moving out of the TP (Fig. 6c). As for the maximum precipitation, MT-MCSs and LT-MCSs, respectively, reach their maximum and minimum in summer, exhibiting opposite subseasonal variations (Fig. 6e). Moreover, the total precipitation exhibits a pronounced peak in both types of MCSs during July (Fig. 6f).

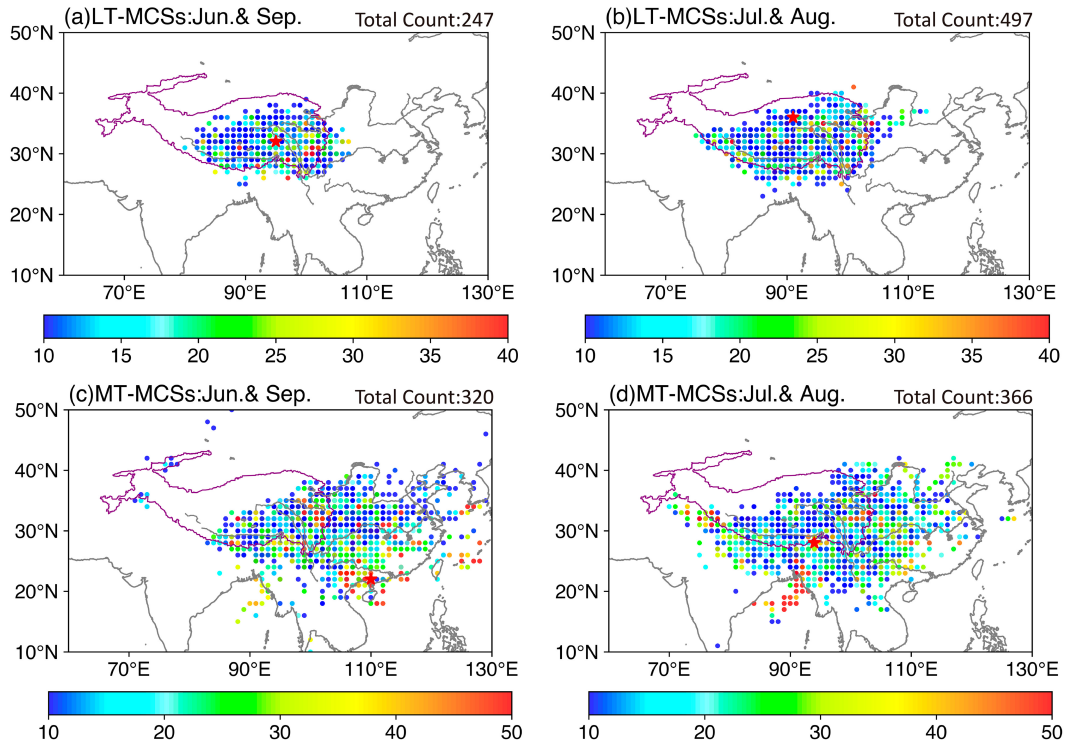


FIG. 8. Spatial distributions of maximum precipitation during (a),(c) transition months (i.e., June and September) and (b),(d) midsummer (i.e., July and August) for (a),(b) LT-MCSs and (c),(d) MT-MCSs. The red star, purple line, and total number in the top-right corner denote the maximum value, the TP, and the number of MCSs, respectively. The maximum precipitation is the mean of the hourly maximum precipitation at each time step of MCSs.

Notably, it can be seen that MCSs generally exhibit the highest occurrences and greatest total precipitation during July over the TP, while during June in the Yangtze River basin and southern China of East Asia (Li et al. 2020; Kukulies et al. 2021; Mai et al. 2021; Yun et al. 2021).

We further investigate monthly variations for MCSs with different movement paths (Fig. 7). For both LT-MCSs and MT-MCSs, the SE path has the highest frequency of occurrence in almost all months, except in May. Moreover, the four movement paths can coexist in midsummer, while the rest of the months are mainly dominated by eastward-moving (SE and NE) MCSs (Figs. 7a,b). There are some notable differences between LT-MCSs and MT-MCSs. For LT-MCSs, the numbers of all the four movement paths increase from May to July and then decrease, while for MT-MCSs, the increase in the number of the SW path corresponds to obvious decreases in the numbers of both the SE and NE paths. The opposite trends (from June to July) in the eastward-moving MCSs between LT-MCSs and MT-MCSs can explain the relatively higher occurrence frequency of LT-MCSs than that of MT-MCSs in midsummer. For movement speed, all paths reach its minimum value during July and August for both LT-MCSs (Fig. 7c) and MT-MCSs (Fig. 7d), which is highly related to the reduction in horizontal winds at 500 hPa (figure not shown). For maximum precipitation of LT-MCSs, the SE and SW paths exhibit stronger subseasonal variation

compared to that of the NE path and thus are more important for the mean results shown in Fig. 7e. For total precipitation of MT-MCSs (Fig. 7h), nearly all the four paths reach their maximum in July. Other properties such as cloud area and duration show consistent subseasonal variations among different paths (figure not shown).

Previous analyses have indicated the remarkable differences of the spatial distribution of maximum precipitation among different movement paths. Because more than 90% of MCSs occur in the period from June to September and MCSs with the SW path are mainly observed in July and August, here we compare the spatial distributions of maximum precipitation between two periods, i.e., midsummer (i.e., July and August) and the transition months (June and September) (Fig. 8). For LT-MCSs (Figs. 8a,b), the difference between the two periods is small given that the distributions of maximum precipitation are similar for different movement paths (Figs. 4a–c). For MT-MCSs (Figs. 8c,d), there exist strong subseasonal variations in the spatial distributions of maximum precipitation. Specifically, during transition months (Fig. 8c), high values of maximum precipitation are located in the eastern part of the TP and southern China, as well as sea areas to the southeast of China. The strong precipitation is jointly contributed by MT-MCSs with the NE and SE movement paths (Figs. 4d,f). During midsummer (Fig. 8d), high values of maximum precipitation are mainly located in the Bay of Bengal

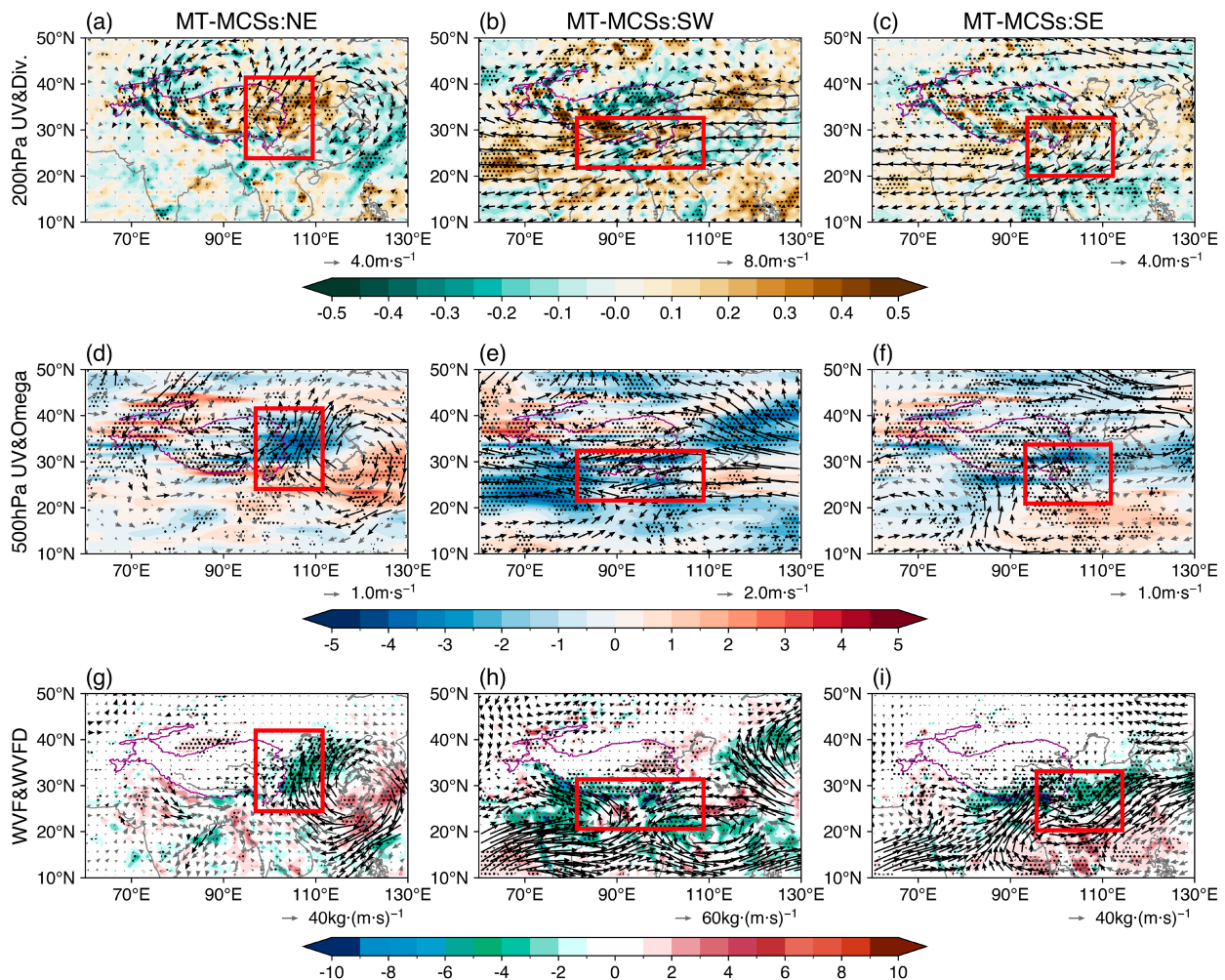


FIG. 9. Daily composite large-scale atmospheric circulation (subtracted by the warm-season mean values from 2001 to 2023) for MT-MCSs. (a)–(c) Horizontal winds (vectors; m s^{-1}) and divergence (shading; 10^{-5} s^{-1}) at 200 hPa. (d)–(f) Horizontal winds (vectors; m s^{-1}) and vertical velocity (shading; hPa s^{-1}) at 500 hPa. (g)–(i) Vertical integral of the divergence of water vapor flux (shading; $10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) and vertical integral of water vapor flux (vectors; $\text{kg m}^{-1} \text{ s}^{-1}$). The black dotted areas and black vectors represent variables that pass the 95% significance t test. The red rectangle denotes the MCS occurrence area corresponding to the path.

due to the high occurrence of MCS with the SW path (Fig. 4e). It is also worth noting that although MT-MCSs with the SE path are still frequently observed during midsummer, their precipitation intensity is lower than that in the transition months. Therefore, the spatial distribution of maximum precipitation during midsummer is dominated by MCS with the SW path.

c. Atmospheric backgrounds associated with the variations of MCSs

Regarding the circulation anomalies of MCSs generated over the TP, the differences are small for LT-MCSs with different movement paths, which all exhibit remarkable easterly wind anomalies (figure not shown). For MT-MCSs, each path exhibits a distinct circulation pattern (Fig. 9). In particular, in the NE path, anomalous cyclonic and anticyclonic systems are present in the mid- and upper troposphere over the TP and

eastern China, respectively (Figs. 9a,d). The anomalous anticyclone not only supplies water vapor to the TP and its downstream regions but also steers the MCSs to move northeast along the southwesterly winds until they reach northern China (Fig. 9g). In the SW path, it can be seen strong anomalous northwesterly winds at 200 and 500 hPa, allowing the MCSs to move southwestward (Figs. 9b,e). As for the SE path, northwesterly wind anomalies dominate the northeastern TP at 200 hPa (Fig. 9c) and the eastern TP at 500 hPa, guiding the southeast movement of MCSs (Fig. 9f). Anomalies in water vapor transport and its convergence also have notable discrepancies among paths. Specifically, in the NE path, anomalous northeastward transport and convergence of water vapor occur in 30° – 40°N from the eastern part of the TP to eastern China (Fig. 9g). In the SW path (Fig. 9h) and SE path (Fig. 9i), water vapor is transported along anomalous cyclonic and anticyclonic systems in the tropical western Pacific,

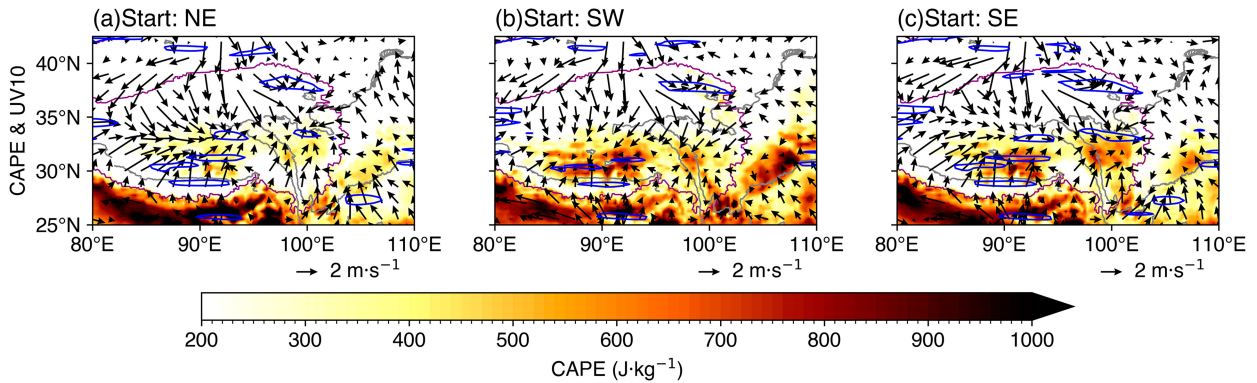


FIG. 10. Hourly composites of 10-m divergence (blue contours; represent values of $-1.2 \times 10^{-5} \text{ s}^{-1}$) and CAPE (shading; J kg^{-1}) at the start time of MT-MCSs with the (a) NE, (b) SW, and (c) SE paths.

forming a zonally distributed water vapor convergence at 20° and 30°N , respectively. Furthermore, in the SW (SE) paths, the water vapor flux anomalies are stronger in low-latitude ocean areas (eastern China), consistent with the spatial distribution of maximum precipitation.

In addition to the large-scale circulation, we further analyze the spatial distributions of CAPE and 10-m divergence (representing surface convergence) at the initiation time of MT-MCSs (Figs. 10a–c). Strong CAPE consistently occurs near surface convergence centers across all paths, providing favorable conditions for MCS initiation, which is consistent with previous studies (Zhang et al. 2014; Chen and Li 2021; Lu et al. 2024). The SE and SW paths generally exhibit higher CAPE values than the NE path, particularly in the southern TP. Moreover, a distinct convergence center is present over the eastern TP for the NE and SE paths, creating especially

favorable environment for convection initiation there (Figs. 3d,f).

Figure 11 presents the Hovmöller diagrams of horizontal winds, vertical velocity, and vorticity at 500 hPa for MT-MCSs with different movement paths. The results indicate that, compared to local atmospheric instability and surface convergence, large-scale circulation is generally more important for the movement paths of MCSs throughout their lifetime (Figs. 11a–c). In addition, for the SE and NE paths, the enhancements of midlevel vertical velocity and vorticity (Figs. 11a,c) downstream of the TP also play crucial roles in enabling MCSs to propagate out of the TP, as previously demonstrated (Chen et al. 2010; Bao and Zhang 2013; Chen et al. 2014; Fu et al. 2021).

The daily composite large-scale atmospheric circulation for MCSs during the midsummer (July and August) and transition

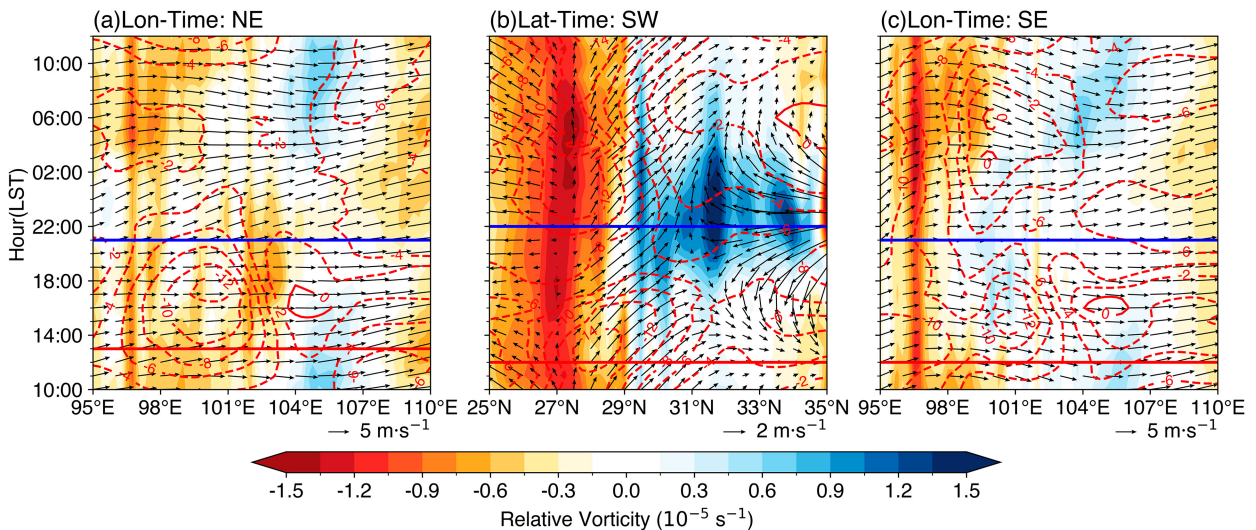


FIG. 11. Hovmöller diagrams of horizontal winds (vectors; m s^{-1}), vertical velocity (red contours; hPa s^{-1}), and vorticity (shading; 10^{-5} s^{-1}) at 500 hPa for MT-MCSs with the (a) NE path (time–longitude distribution; averaged between 30° and 40°N), (b) SW path (time–latitude distribution; averaged between 80° and 100°E), and (c) SE path (time–longitude distribution; averaged between 25° and 35°N). The red line and blue lines are the median of MCS start time and out time, respectively. All times are in LST (i.e., UTC + 6 h).

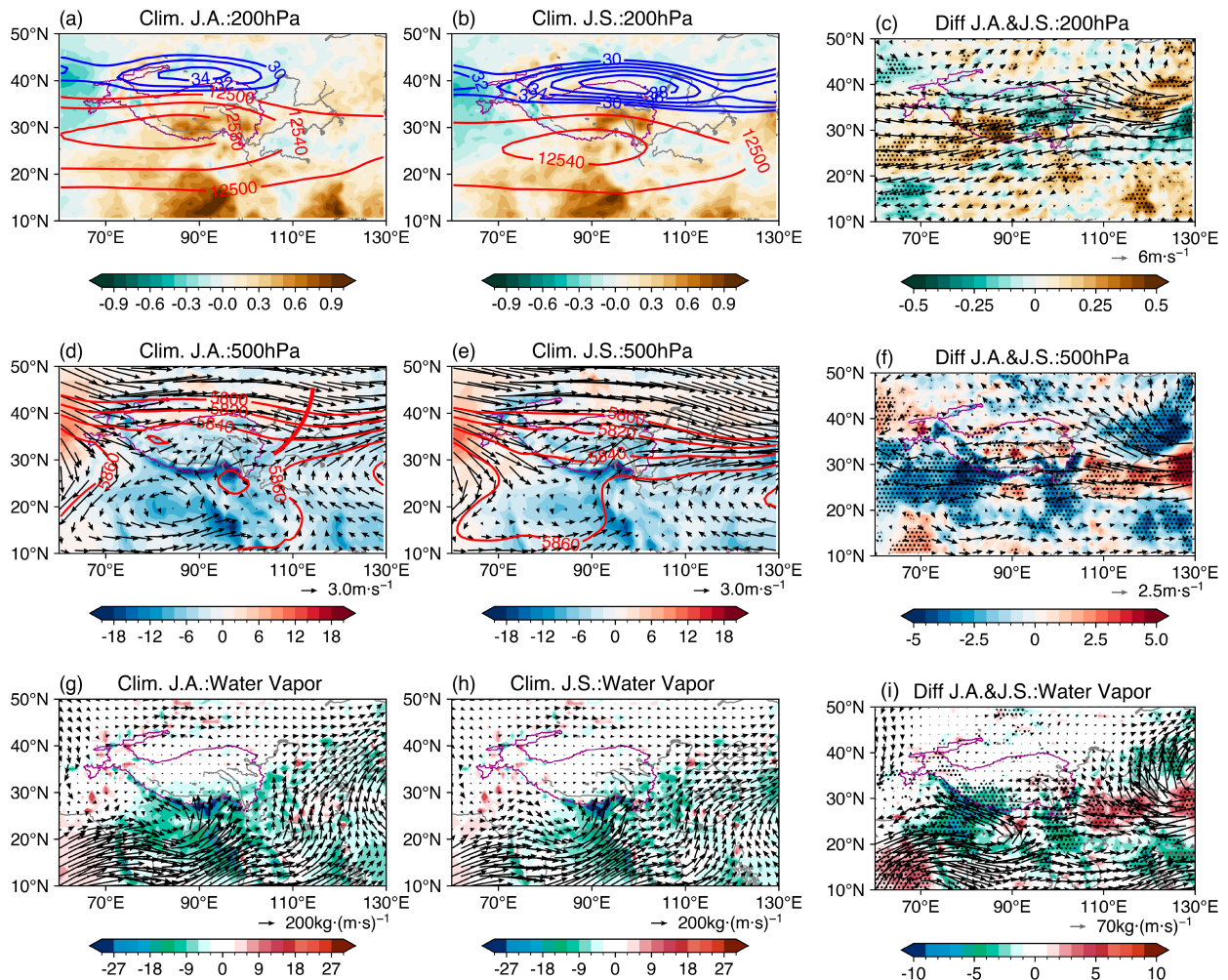


FIG. 12. Daily composite large-scale atmospheric circulation for MCSs during (a),(d),(g) July and August and (b),(e),(h) June and September and (c),(f),(i) their difference from 2001 to 2023. (a)–(c) Geopotential height (red contours; 12 500 gpm), horizontal wind speeds (blue contours; $\geq 30 \text{ m s}^{-1}$), horizontal winds (vectors; m s^{-1}), and divergence (shading; 10^{-5} s^{-1}) at 500 hPa. (d)–(f) Geopotential height (red contours; gpm), horizontal winds (vectors; m s^{-1}), and vertical velocity (shading; hPa s^{-1}) at 500 hPa. (g)–(i) Vertical integral of the divergence of water vapor flux (contours; $10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) and vertical integral of water vapor flux (vectors; $\text{kg m}^{-1} \text{ s}^{-1}$). The black dotted areas and black vectors in (c), (f), and (i) represent differences that pass the 95% significance t test.

months (June and September) are shown in Fig. 12. For both the two periods, the TP lies to the north of the SAH and to the south of the subtropical westerly jet (SWJ), where strong wind speeds and temperature gradients generate intense divergence at 200 hPa (Figs. 10a,b). At 500 hPa (Figs. 12d,e), the TP is governed by midlatitude short-wave troughs or ridges. Besides, the western Pacific Ocean subtropical high can also be found in eastern China. Meanwhile, water vapor transport from the southwesterly winds can be detected during all months of the warm season (Figs. 12g,h). These systems, which create favorable dynamic and thermodynamic environments for the generation and propagation of MCSs, are featured by remarkable subseasonal variations (Zhu and Chen 2003; Ueno et al. 2011; Chen and Li 2021). During midsummer (Fig. 12c), the strengthening of SAH and the weakening of SWJ contributes to northeasterly wind anomalies on the

TP and anomalous divergence in the southern part of the TP. At 500 hPa, the weakening and northward shift of the westerly trough (red contour line at 5840 gpm) as well as the westward shift of the western Pacific Ocean subtropical high (red contour line at 5880 gpm) (Fig. 12d vs Fig. 12e) result in anomalous easterly winds and upward motions between 20° and 30°N (Fig. 12f). In differences of the water vapor, anomalous westward transport of water vapor is accompanied by enhanced divergence of water vapor from the eastern part of the TP to eastern China and convergence in the southern part of the TP and South Asia (Fig. 12j). These changes lead to decreased number of eastward-moving (SE plus NE) MT-MCSs (Fig. 7b) and a southwesterly shift of high value centers of maximum precipitation (Figs. 8c,d) during midsummer compared to during transition months.

Previous studies have shown that atmospheric intraseasonal oscillations can largely influence precipitation anomalies in

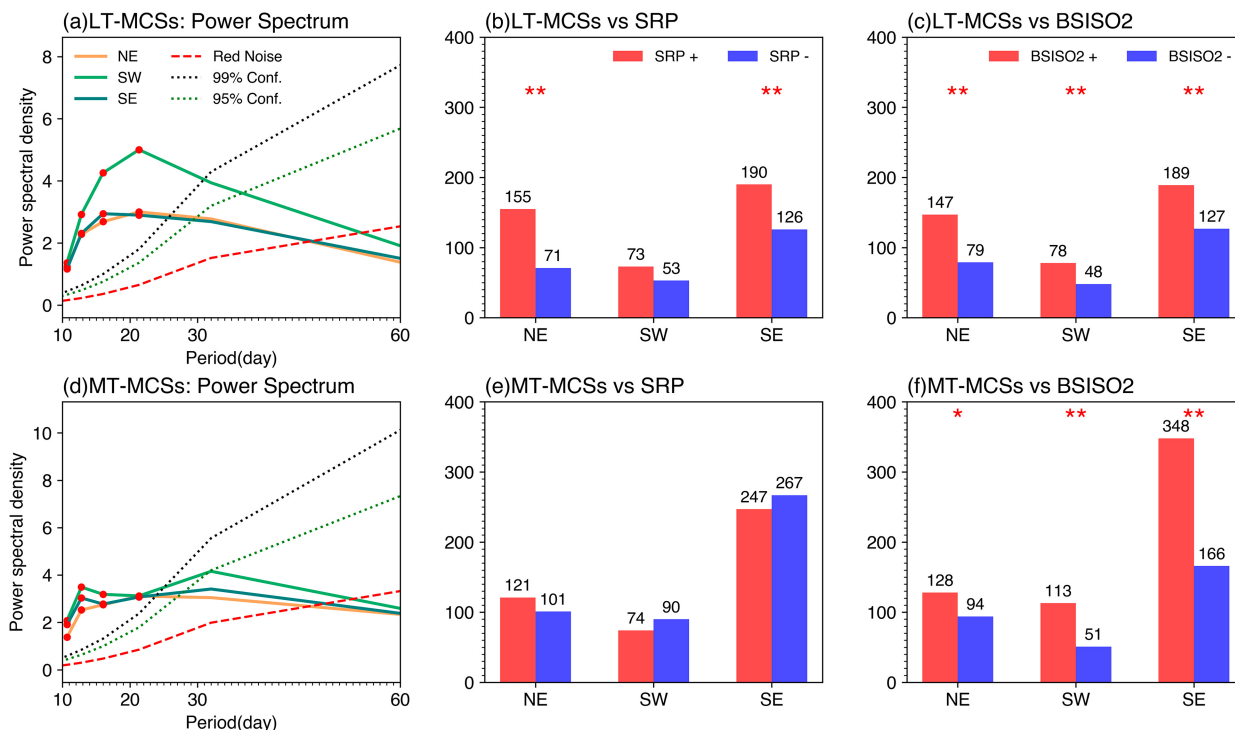


FIG. 13. Power spectral density of the intraseasonal variability for normalized occurrence of (a) LT-MCSs and (d) MT-MCSs with different paths. Occurrence of MCSs during positive/negative phases (red/blue bars) of (b),(e) SRP and (c),(f) BSISO2 for different paths (b),(c) LT-MCSs and (e),(f) MT-MCSs. The red dots in (a) and (d) represent the signal exceeding the 95% significance level t test. The * and ** in (b), (c), (e), and (f) denote significance levels of 95% and 99% based on the binomial distribution, respectively. The numbers in (b), (c), (e), and (f) represent the occurrences of MCSs at corresponding phases.

East Asia (Luo et al. 2013; Liu et al. 2022; W. Li et al. 2023; B. Liu et al. 2024; Zhu et al. 2025). In this study, the power spectrum analysis of the intraseasonal variability in the occurrence of MCSs reveals significant peaks in the period of 10–20 day for different types and paths of MCSs (Figs. 13a,d). We further examine the relationship between MCS occurrences and two large-scale indices, i.e., the Silk Road pattern (SRP) and the boreal summer intraseasonal oscillation (BSISO), which represent the westerly wave train and low-latitude 10–30-day oscillations, respectively (Ding and Wang 2005; Lee et al. 2013; W. Li et al. 2023; Zhang and Duan 2023). Figures 13e and 13f present the composites of MCS occurrences at different phases of the BSISO2 index (i.e., the 10–30-day mode of BSISO), suggesting that MCSs along all paths are significantly correlated with the phase of BSISO2. This relationship likely reflects the enhanced water vapor transport associated with the westward and southward displacement of the subtropical high during the positive phase of BSISO (W. Li et al. 2023). By contrast, only eastward-moving LT-MCSs (SE and NE paths) show significant correlations with the phase of SRP (Fig. 13b).

4. Summary and discussion

Based on half-hourly GPM IMERG satellite data for the period 2001–23, this study statistically investigates MCSs generated over the TP during warm seasons. The spatial

and temporal characteristics of MCS movement paths, associated precipitation features, and large-scale atmospheric environments are categorized and analyzed.

The number of LT-MCSs over the TP is generally comparable with that of MT-MCSs. For both types, the primary movement paths are SE, NE, and SW, accounting for 50%, 30%, and 15% of the total number of MCSs, respectively. For LT-MCSs, eastward-moving MCSs (SE plus NE) travel faster and exhibit stronger maximum precipitation but lower cloud area and total precipitation compared to westward-moving MCSs (SW plus NW). For MT-MCSs, the SW path possesses higher values in terms of all the investigated properties (i.e., faster movement speed, larger cloud area, stronger precipitation, and so on) compared to the other movement paths. It is apparent that the MCSs generated over the south and east part of TP tend to move out of TP along the south and east path, respectively, while those in the center TP are more likely stay in TP. In addition, the spatial distribution of maximum precipitation of LT-MCSs is largely path independent. Differently, the maximum precipitation of MT-MCSs gradually increases with the distance away from the TP for the SE and SW paths but decreases for the NE path. At diurnal time scale, both LT-MCSs and MT-MCSs typically initiate between 1000 and 1400 LST but differ markedly in terms of other properties. For instance, LT-MCSs and MT-MCSs reach their peak precipitation rate at around 1800LST and between 0000 and 0600 LST, respectively.

MT-MCSs and LT-MCSs show remarkable subseasonal variation, the occurring frequencies increase from May to July and then decrease. However, the MT-MCSs and LT-MCSs show opposite subseasonal trend in the maximum precipitation, reaching their highest and lowest values in summer, respectively. Notably, the occurrence of LT-MCSs is higher than MT-MCSs during midsummer (i.e., July and August) while lower in the other 3 months. For both MT-MCSs and LT-MCSs, the four movement paths coexist in midsummer, while the rest of the months is dominated by eastward-moving (SE and NE) MCSs. For LT-MCSs, all paths increase simultaneously, while for MT-MCSs, increase in SW path is accompanied by decreases in SE and NE, which explains the relatively lower occurrence frequency of MT-MCSs than that of LT-MCSs in midsummer. In addition, there exists strong subseasonal variations in the spatial distributions of maximum precipitation for MT-MCSs. Specifically, during transition months (June and September), high values of maximum precipitation are located in the eastern part of the TP and sea areas to the southeastern China, which are jointly contributed by MCSs with the NE and SE movement paths. During midsummer, high values of maximum precipitation are mainly located in the Bay of Bengal due to the high occurrence of MCS with the SW path.

The movement paths of MCSs are dominated by the guiding winds in the mid-upper troposphere, especially for MT-MCSs. In detail, the NE, SW, and SE paths are accompanied by anomalous southwesterly, northeasterly, and northwesterly in the TP and adjacent regions, respectively. In the low troposphere, anomalous water vapor flux is present in low-latitude ocean areas and eastern China for MT-MCSs with the SW and SE paths, consistent with the spatial distributions of maximum precipitation. In addition, the locations of MCS generations are related to the spatial distributions of atmospheric instability and surface convergence, with southward- and eastward-moving MCSs exhibiting high instability over the southern TP and a distinct convergence center over the eastern TP, respectively.

This study quantitatively studied the characteristics of warm-season MCSs with different movement paths generated over the TP. However, several issues remain unresolved. First, the detection of MCSs can be affected by uncertainties associated with the applied tracking algorithms and satellite retrieval data (Kukulies et al. 2023; Feng et al. 2025). For example, when using higher thresholds for CCS area and rain rate (Kukulies et al. 2021), the numbers of MCSs are largely reduced. Nevertheless, we found similar spatial-temporal distributions of MCS properties for both LT-MCSs and MT-MCSs when using different thresholds (figure not shown). Second, MCSs consist of both convective and stratiform regions, which are featured by different cloud microphysical processes (Houze 2004, 2012; Chen et al. 2020; Schumacher and Rasmussen 2020). How the convective and stratiform processes vary when MCSs move out of the TP is not well understood. In addition, previous studies revealed that MCSs in East Asia have intensified over the past two decades (Guo et al. 2023; P. Li et al. 2023). Our primary results suggest that compared to LT-MCSs, MT-MCSs have a more pronounced trend of increase, especially for those along the NE

path (figure not shown). The variations in MT-MCSs might impact regional climate over downstream areas of TP, which deserve further investigations. Addressing these questions will require further investigation.

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Data availability statement. The NASA infrared brightness temperature can be downloaded from https://disc.gsfc.nasa.gov/datasets/GPM_MERGIR_1/summary, and GPM Integrated Multi-satellite Retrievals for GPM (IMERG) V06 B precipitation can be found at https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGHH_07/summary. The latest version of the hourly ERA5 reanalysis data at single and pressure levels can be accessed through Copernicus Climate Data Store at <https://cds.climate.copernicus.eu#!/home>. The code for the MCS tracking algorithm is provided by Feng et al. (2023), which can be downloaded from <https://github.com/FlexTRKR/PyFLEXTRKR>.

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