Mesoscale Convective System Precipitation Characteristics over East Asia. Part I: Regional Differences and Seasonal Variations

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ABSTRACT: Mesoscale convective systems (MCSs) play an important role in modulating the global water cycle and energy balance and frequently generate high-impact weather events. The majority of existing literature studying MCS activity over East Asia is based on specific case studies and more climatological investigations revealing the precipitation characteristics of MCSs over eastern China are keenly needed. In this study, we use an iterative rain cell tracking method to identify and track MCS precipitation during 2008–16 to investigate regional differences and seasonal variations of MCS precipitation characteristics. Our results show that the middle-to-lower reaches of the Yangtze River basin (YRB-ML) receive the largest amount and exhibit the most pronounced seasonal cycle of MCS precipitation in eastern China. MCS precipitation over YRB-ML can exceed 2.6 mm day^{-1} in June, contributing over 30.0% of April–July total rainfall. Particularly long-lived MCSs occur over the eastern periphery of the Tibetan Plateau (ETP), with 25% of MCSs over the ETP persisting for more than 18 h in spring. In addition, spring MCSs feature larger rainfall areas, longer durations, and faster propagation speeds. Summer MCSs have a higher precipitation intensity and a more pronounced diurnal cycle except for southeastern China, where MCSs have similar precipitation intensity in spring and summer. There is less MCS precipitation in autumn, but an MCS precipitation center over the ETP still persists. MCSs reach peak hourly rainfall intensities during the time of maximum growth (a few hours after genesis), reach their maximum size around 5 h after genesis, and start decaying thereafter.

KEYWORDS: Asia; Convective storms/systems; Mesoscale systems; Precipitation; Rainfall; Seasonal variability

1. Introduction

Mesoscale convective systems (MCSs) are organized deep convective clouds that aggregate and interact to induce a nearly contiguous and extensive area of precipitation, covering a horizontal scale of hundreds to a few thousand kilometers and lasting several hours or even longer (Houze and Betts 1981; Zipser 1982; Houze et al. 1989; Laing and Fritsch 1997; Trapp 2013; Houze 2018). MCSs contribute a large portion of total precipitation in the tropical and midlatitude regions and play a key role in the global hydrological cycle, large-scale circulations, and energy balance (Houze 1989, 2004, 2018; Doswell 2003; Feng et al. 2019; Song et al. 2019; R. Yang et al. 2019). Besides, MCSs can generate high-impact damaging weather events such as lightning, gusty winds, damaging hail, and heavy rainfall, which frequently cause fatalities and economic losses (Doswell et al. 1996; Zipser et al. 2006; Trapp 2013; Feng et al. 2016; Houze 2018).

MCSs can be identified and tracked by multiple atmospheric fields, including but not limited to cloud-related variables such as cloud-top brightness temperature derived from satellite

infrared images (Yang et al. 2015; Chen et al. 2019; Q. Yang et al. 2019), midtropospheric vorticity (Wang et al. 2011), Doppler radar composite reflectivity (Zheng et al. 2013), and surface precipitation (Houze 2004, 2018; Clark et al. 2014; Prein et al. 2017a,b). Maddox (1980) first clearly identified mesoscale convective complexes (MCCs), an extreme subset of MCSs, by using satellite infrared measurements. Laing and Fritsch (1997) systematically investigated MCC occurrence and development from a global perspective. They found that large and long-duration summertime MCCs prefer to form and develop downstream of huge mountain ranges, including the tropical West African monsoon (WAM) region (downstream of the Ethiopian Plateau; Mathon et al. 2002; Taylor et al. 2017; Trzeciak et al. 2017; Pante and Knippertz 2019), the central United States (to the east of the Rocky Mountains; Machado et al. 1998; Carbone et al. 2002; Feng et al. 2016, 2018, 2019; Yang et al. 2017; Song et al. 2019), and the East Asian monsoon (EAM) region (downstream of the Tibetan Plateau; Li et al. 2008; Sugimoto and Ueno 2010; Zheng et al. 2013; Yang et al. 2015). Previous studies have indicated that MCSs have become more intense and frequent under global warming. Taylor et al. (2017) pointed out that the frequency of extreme MCSs over the Sahelian region of WAM tripled since the 1980s, and has been highly correlated with the rapid intensification of Saharan warming caused by anthropogenic forcing. Feng et al. (2016) showed that the major proportion of both total and extreme

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precipitation over the United States Great Plains are dominated by MCSs in spring, and revealed that intense and long-lived MCSs became more frequent during the last three decades. A better understanding of MCSs' physical mechanisms is necessary to improve the simulation of MCSs in weather and climate models aiming to mitigate their potential damaging impacts (Doswell 2003; Trapp 2013; Prein et al. 2017b; Houze 2018).

Numerous studies have shown the importance of large-scale environments on the genesis and development of MCSs, through dynamical and thermodynamical processes (Ueno et al. 2011; Zheng et al. 2013; Yang et al. 2015, 2017; Prein et al. 2017b; Feng et al. 2019; Song et al. 2019; R. Yang et al. 2019). In the tropics, Mapes et al. (2009) indicated that the Madden-Julian oscillation (MJO) has a varying population of convective systems, and MCSs frequently occur during the active MJO phase. In the midlatitudes, MCSs to the east of the Rocky Mountains systematically generate and develop ahead of large-scale troughs in the westerlies, accompanied by an enhanced warm and moist low-level jet from lower latitudes (Feng et al. 2016, 2019; Yang et al. 2017; Song et al. 2019). Over the EAM region, the relationship between MCSs and large-scale monsoonal circulations exhibits a complex interplay. Fu et al. (2011) found that MCSs over the Tibetan Plateau prefer to move eastward and affect downstream regions more easily when the upper-level (~ 200 hPa) jet shifts southward and the midlevel (~ 500 hPa) trough moves eastward. Over the eastern periphery of the Tibetan Plateau (see Fig. 1), MCSs predominantly form and strengthen accompanied by a lower-to-middle-tropospheric southwest vortex, a stronger low-level jet, and a larger convective available potential energy (Fu et al. 2011; Chen et al. 2014; Jiang et al. 2014; Li et al. 2019). Moreover, the low-level cyclonic vorticity favors the MCSs' sustenance over that region (Q. Yang et al. 2019). Over the middle-to-lower reaches of the Yangtze River valley (see Fig. 1), the large-scale background circulation of MCSs is usually dominated by the subtropical quasi-stationary mei-yu front, with large meridional gradients of equivalent potential temperature and moisture, a low-level wind shear line, and mei-yu frontal lifting (Sun et al. 2010; Zhang and Zhang 2012; Chen et al. 2017; Li et al. 2019; Guan et al. 2020).

At the same time, MCSs exhibit strong feedback in modulating surrounding large-scale circulations through "top-heavy" diabatic heating (Trapp 2013; Yang et al. 2017; Houze 2018; Feng et al. 2018, 2019; Song et al. 2019). During the MJO active phase, MCSs account for a large proportion of total precipitation (Virts and Houze 2015), and one of the most prominent features during this active phase is top-heavy total diabatic heating induced by MCSs' large-scale stratiform rainfall (Barnes et al. 2015). Furthermore, R. Yang et al. (2019) revealed that upshear-moving MCSs can significantly strengthen the westerly wind burst over the Maritime Continent. In the midlatitudes, Yang et al. (2017) demonstrated that long-lived MCSs to the east of the Rocky Mountains can strengthen the quasi-balanced mesoscale vortex to maintain their intensity and strengthen the environmental trough through diabatic heating.

The organization and spatiotemporal evolution of MCSs are affected by distinct land surface and atmospheric conditions (Houze et al. 1989; Davis 2001; Carbone et al. 2002; Yang et al.

FIG. 1. Topography over eastern China and four subregions focused in this study. The red contour indicates the Tibetan Plateau (TP), where the topography exceeds 2800 m. Here the orange rectangle indicates the eastern periphery of the Tibetan Plateau (ETP), the blue rectangle indicates the middle-to-lower reaches of the Yangtze River Basin (YRB-ML), the red rectangle indicates southeastern China (SEC), and the pink rectangle indicates the lower reaches of the Yellow River Basin (LYB).

2015; Zhang et al. 2019). Most existing literature on MCSs is based on U.S. or tropical MCSs whereas MCSs over eastern China have drawn relatively less attention due to the lack of observations at high temporal and spatial resolution in the past. The majority of literature studying eastern China's MCSs is based on case studies and focuses on synoptic aspects.

In this paper, we aim to provide a climatological overview of MCSs over eastern China and focus on the regional and seasonal characteristics of MCS mean and extreme precipitation, as well as the dynamic evolution of MCS properties. For this aim, we apply an iterative rain cell tracking (Moseley et al. 2013, 2019) method to identify and track MCS precipitation systems during the period 2008–16.

The remainder of this paper is organized as follows. The observation data and analysis methods are introduced in section 2. In section 3, we describe the main results, including MCS tracks, frequency, and precipitation, and their contributions to total rainfall, regional differences and seasonal variations of MCS precipitation characteristics, and the dynamic evolution of the MCS properties over eastern China. Finally, a summary and a discussion are given in section 4.

2. Data and methodology

a. Observation dataset

We used a merged rain gauge–satellite gridded hourly precipitation dataset for China (Pan et al. 2012; Shen et al. 2014), developed by the National Meteorological Information Center (NIMC), China Meteorological Administration (CMA). It

combines over 30 000 hourly surface rainfall measurements from the CMA's rain gauge network with the Climate Prediction Center's morphing technique (CMORPH; Joyce et al. 2004) satellite-retrieved precipitation product by using the probability density function optimal interpolation (PDF-OI) method (Pan et al. 2012; Yu et al. 2013). This product covers the studying period from 2008 to 2016 (Shen et al. 2014), with a horizontal grid spacing of approximately 10 km.

b. Iterative rain cell tracking method

We use precipitation to identify and track MCSs due to its high socioeconomic relevance and the availability of the merged rain gauge–satellite gridded hourly precipitation dataset for China. Our MCS tracking approach is similar to those used over the United States such as in Davis et al. (2009), Clark et al. (2014), and Prein et al. (2017a,b). These approaches use the MCS definition proposed by Houze (2004), which identified MCSs as continuous precipitation regions that live for several hours and have a minimum diameter of 100 km in at least one direction.

We apply an “iterative rain cell tracking” (IRT) algorithm to track life cycles of MCSs in space and time (Moseley et al. 2013, 2019). In a first step, connected areas with surface precipitation exceeding a predefined threshold are detected as objects for each time step individually. For each object, the weighted center of the object, the area, and the mean and maximum surface precipitation intensity within rainfall area are recorded. The weighted center of the object will also be used to calculate the composite of MCSs at peak stage, where the “peak stage” is defined as the time when an MCS has the most intense precipitation through the lifetime. In this study, we focus on relatively long-lived (duration ≥ 6.0 h) and intense MCSs due to their high socioeconomic relevance: an MCS is defined as a single entity with intense precipitation (≥ 3.0 mm h⁻¹) covering an area exceeding 3600 km² (this is set to exclude too small, non-MCS storms, and allows us to track storms that have a minimum length of 100 km and a minimum width of 36 km), which is feasible and aligns well with Houze (2004, 2018). Additional sensitivity tests with 5.0 and 2.5 mm h⁻¹ have shown that different thresholds can affect the number of identified MCS, but the overall MCS properties remain relatively robust. From these sensitivity tests, we conclude that an intermediate threshold of 3.0 mm h⁻¹ is best suited in this study, as on the one hand it is high enough to detect areas of intense rainfall and exclude drizzle, but on the other hand it is moderate enough to detect MCSs early in their developing stage. In this study, the start time of an MCS is defined as the first time that the system attains the MCS criteria we have established.

The algorithm checks for overlaps of each object with objects in the previous and the subsequent time step, and records the concerning object identifiers. If an object overlaps with more than one object at the previous or subsequent time step, the two largest ones are recorded, and others are ignored. In a convergent iterative process, the object identification is repeated several times to account for the fact that objects move in time, which can distort the overlap detections. In each subsequent iteration step, the advection velocity of the objects is estimated and considered for the detection process in the

subsequent iteration. In a final step, overlapping objects are combined to the same track.

c. Analysis methods

In this study, we first use IRT method to identify and track MCS over eastern China at every time step (1-h time interval) during the study period; after all relevant MCSs at each time step are detected, tracked, and labeled by the IRT method, we bin the hourly total precipitation into MCS precipitation and non-MCS precipitation, according to the mask file of all MCSs generated by the IRT method; then we investigate MCS precipitation characteristics, particularly focusing on the regional differences and seasonal variations of MCS precipitation over eastern China.

MCS precipitation frequency (unit: number of hours per season) at each grid point is defined as the number of hours in each season that have MCS precipitation (identified and tracked by using the method described in section 2b). The average (maximum) hourly precipitation is defined as the average (maximum) precipitation rate within the MCS rainfall area at each hourly time step. The specific name and abbreviation of each subregion is shown in Fig. 1. We focus on MCS precipitation in three seasons, spring [March–May (MAM)], summer [June–August (JJA)], and autumn [September–November (SON)], during the studying period from 2008 to 2016.

3. Results

a. MCS tracks, precipitation frequency, and precipitation amount and its contributions to total rainfall

All MCS tracks and spatial distributions of MCS precipitation frequency in each season during the studying period are shown in Fig. 2. A total of 1085, 2060, and 651 long-lived and intense MCSs (duration ≥ 6 h) over the eastern China mainland (21.0°–38.0°N, 102.5°–121.5°E) were tracked in spring, summer, and autumn during the study period (2008–16), averaging 120, 228, and 72 in each spring, summer, and autumn per year, respectively (Figs. 2a–c). This large sample of MCSs allows us to carry out a robust statistical analysis of MCS precipitation characteristics over eastern China.

More importantly, there are distinct regional differences and notable seasonality on the spatial distributions of MCS precipitation frequency (Figs. 2d,e). MCS precipitation can be found in spring (with an average value of 9.0 h over the eastern China mainland) and occurs most frequently in summer (14.1 h), then it becomes relatively less in autumn (4.3 h). In spring, MCSs preferentially occur over mountainous regions, such as the Nanling Mountains and Wuyi Mountains (the specific locations have been indicated in Fig. 1). Most MCSs move eastward and propagate faster over all subregions compared with those in summer and autumn (Table 1). The MCS precipitation frequency can exceed 35 h yr⁻¹ in a large area of southeastern China (SEC) and lower-to-middle reaches of the Yangtze River basin (YRB-ML; Fig. 2d), with average propagation speeds of 53.6 and 60.0 km h⁻¹ over these two regions (Table 1), respectively. In summer, a northward migration of MCS activity can be seen; not only can MCSs still occur over

FIG. 2. (a)–(c) MCS tracks and (d)–(f) spatial distributions of MCS precipitation frequency (unit: h yr^{-1}) in (a),(d) spring (MAM), (b),(e) summer (JJA), and (c),(f) autumn (SON) during the study period from 2008 to 2016. The red contour indicates the TP, where the topography exceeds 2800 m.

the western part of SEC and YRB-ML, but another MCS population center arises over the eastern periphery of the Tibetan Plateau (ETP; Fig. 2e). In autumn, MCS activity decreases over the whole of eastern China, but it still exhibits a notable center with a maximum between 21 and 25 h yr^{-1} over the ETP (Fig. 2f). Interestingly, MCSs over YRB-ML have

larger propagation speeds, compared with other subregions (Table 1). We hypothesize that the quicker propagation speed is related to the background large-scale circulations (such as subtropical mei-yu front) over YRB-ML, which has been investigated in previous studies focusing on extreme precipitation events in a narrow latitudinal band along the mei-yu front

TABLE 1. The average propagation speed of MCS precipitation systems and the number of hours when MCS has extreme precipitation (the maximum hourly precipitation within the rainfall area at each time step exceeds 50.0 mm h^{-1}) over four subregions in spring, summer, and autumn. Here ETP, YRB-ML, SEC, and LYB respectively indicate the eastern periphery of the Tibetan Plateau (27.0° – 34.0°N , 102.5° – 110.5°E), the middle-to-lower reaches of the Yangtze River Basin (27.0° – 33.0°N , 110.5° – 121.5°E), southeastern China (21.0° – 27.0°N , 102.5° – 117.5°E), and the lower reaches of the Yellow River Basin (33.0° – 38.0°N , 110.5° – 120.0°E).

	MCSs propagation speed (km h^{-1})			No. of hours having extreme precipitation		
	Spring	Summer	Autumn	Spring	Summer	Autumn
ETP	55.4	43.0	42.8	49	185	19
MY	60.0	49.2	52.9	34	193	9
SEC	53.6	44.8	47.5	186	150	14
LYB	59.8	45.5	46.3	0	126	10

(Li et al. 2019; Guan et al. 2020). Another reason could be the weaker orography in this region. The details of the relative roles of environmental circulations and underlying surface in modulating MCS movement features warrant further study.

The spatial distributions of MCS precipitation (Figs. 3a–c) and its contribution to total precipitation (Figs. 3d–f) are shown in Fig. 3. The overall pattern of MCS precipitation amount is quite consistent with the frequency of MCS occurrence (Fig. 2). Two MCS precipitation centers along the Nanling Mountains and Wuyi Mountains can be found in spring (Fig. 3a), and MCS precipitation contributes to over 45.0% to the total rainfall over some regions of SEC (along the Nanling Mountains; Fig. 3d). In summer, MCS precipitation extends to northward (including the lower reaches of the Yellow River basin, hereafter LYB for short) and covers a wider area over eastern China, compared with that in spring (Fig. 3b). Meanwhile, another MCS rainfall center shows up over the ETP (Fig. 3b) and contributes 45.0%–50.0% to total rainfall in some regions of the ETP (Fig. 3e). These results indicate that the long-lived and intense MCSs play an important role in the water cycle over eastern China during warm seasons (Figs. 3a,b and 3d,e). In autumn, the MCS precipitation weakens and gradually disappears over SEC, YRB-ML, and LYB (Fig. 3c). The MCS precipitation center over the ETP persists and contributes around 20.0%–30.0% within some areas of the ETP (Fig. 3f), but the magnitude also shows a significant decrease compared with that in summer (Fig. 3c).

We then further investigate the seasonality of total precipitation, MCS precipitation, and MCS contribution to total rainfall averaged over each subregion (Fig. 4). All four subregions exhibit a significant seasonal cycle (Figs. 4a,b) associated with different large-scale circulations due to the monsoonal march and retreat (Ding and Chan 2005). MCS precipitation in SEC increases from March to June and has the largest amount in May (1.7 mm day^{-1}) and June (1.9 mm day^{-1} ; Fig. 4b), and it contributes 25.1% and 21.9% to the total rainfall in May and June (Fig. 4c), respectively. MCS precipitation occupies only 13.7% and 13.4% in July and August over SEC (Fig. 4c), indicating that considerable

short-duration non-MCS precipitation appears due to late-afternoon surface heating during mid-to-late summer over SEC.

YRB-ML has experienced the largest MCS precipitation amount among all the subregions (Fig. 4b). MCS precipitation can exceed 2.6 mm day^{-1} averaged over YRB-ML in June and it contributes over 30.0% to total rainfall from midspring to midsummer (from April to July), and then it gradually decreases in the following months (Figs. 4b,c). ETP has relatively more MCS precipitation in June (1.6 mm day^{-1}) and July (1.8 mm day^{-1} ; Fig. 4b), and MCS fraction of total rainfall is 31.5% and 34.1% in these two months (Fig. 4c). Also, MCS precipitation could persist over ETP even in early autumn (September; 1.1 mm day^{-1} ; Fig. 4b) and contributes 26.7% to the total rainfall (Fig. 4c). LYB has considerable MCS precipitation only in July (1.5 mm day^{-1}) and August (1.0 mm day^{-1} ; Fig. 4b), which is mainly due to the progression of the monsoonal rainbelt (Wang 2006; Ding 2007), and the MCS fraction of total rainfall is 32.8% and 26.6% in these two months (Fig. 4c), respectively. Except for these two months, both total rainfall and MCS precipitation remain low over LYB (Figs. 4a,b).

b. MCS precipitation characteristics

MCS statistical properties, including MCS lifetime, rainfall area, and average and maximum hourly precipitation over four subregions in three different seasons, are shown in Fig. 5. In general, MCSs over the ETP have a relatively longer duration than that over other subregions; 25% of MCSs over the ETP last 18 h or longer in spring (Fig. 5a). Springtime MCSs have larger rainfall areas in all subregions compared to summer and autumn MCSs (Fig. 5b). In summer, MCSs over YRB-ML have a larger size compared to the other three subregions (Fig. 5b). Summertime MCSs have a stronger precipitation intensity in both average and maximum hourly precipitation almost over all of eastern China, except for SEC, where the springtime and summertime MCSs have similar precipitation intensity in both hourly average and maximum value (Figs. 5c,d). Summertime MCSs over LYB have a stronger precipitation intensity; around 25.0% of MCS maximum hourly precipitation exceeds 30.0 mm h^{-1} (Fig. 5d).

As we noted above, MCSs can exhibit distinct spatiotemporal properties over different regions. Meanwhile, the large-scale monsoonal circulations dramatically change along with EAM march and retreat (Ding and Chan 2005; Wang 2006; Ding 2007). Do MCSs show different characteristics of propagation over different subregions in different seasons? We further investigate the propagation of MCS precipitation over southern China [a time–longitude cross section of the meridionally (21° – 27°N) mean MCS precipitation of all days, with and without precipitation; Figs. 6a–c] and along the Yangtze River [the corresponding result of the meridionally (27° – 33°N) averaged; Figs. 6d–f] in different seasons. MCSs over southern China initiate at 105.0°E in the late afternoon [around 1600–1800 local solar time (LST)] and propagate eastward. Precipitation maximizes around midnight to morning (0200–0900 LST) along the Nanling Mountains (around 110.0°E , shown in Fig. 1) mountainous region in both spring and summer

FIG. 3. (a)–(c) Spatial distributions of MCS precipitation (unit: mm day^{-1}) and (d)–(f) MCS contribution to total precipitation (unit: %) in (a),(d) spring, (b),(e) summer, and (c),(f) autumn. The black contour indicates the TP, where the topography exceeds 2800 m.

(Figs. 6a,b). In summer, MCSs stop propagating eastward around 111.5°E and there is less MCS precipitation to the east of 111.5°E (Fig. 6b). In autumn, MCS activity gradually weakens and there is less MCS precipitation over southern China (Fig. 6c).

Along the Yangtze River, springtime MCSs have a midnight to morning (0200–0900 LST) precipitation peak over the “second-step” terrain region (i.e., over the Daba Mountains

and Wu Mountains, located at around 105.0° – 110.0°E in Fig. 1), the other MCS rainfall peak is to the east of 112.5°E but it does not exhibit a clear diurnal variation (Fig. 6d). Summertime MCSs initiate in the late afternoon (around 1600 LST) in the eastern foothills of Tibetan Plateau (around 100.0°E) and propagate eastward to the second-step terrain region until 110.0°E (Fig. 6e). Another summertime MCS precipitation peak occurs in the early morning (0700–0900 LST) over the

FIG. 4. Monthly (a) total precipitation (unit: mm day^{-1}), (b) MCS precipitation (unit: mm day^{-1}), and (c) MCS contribution to total precipitation (unit: %) averaged over four subregions from March to November.

YRB-ML (Fig. 6e). Autumn MCSs show an early morning (0400–0800 LST) precipitation peak over the second-step terrain region (Fig. 6f).

Figure 7 shows the diurnal variation of both MCS precipitation and non-MCS (defined as the total precipitation minus MCS precipitation) over the four subregions in different seasons. MCS precipitation (solid lines) over ETP has a nighttime peak (0300–0400 LST; Fig. 7a) due to the internal oscillation of the low-level wind and an enhanced low-level moisture transport (Chen et al. 2010; Chen et al. 2013), and it decreases quickly after sunrise (around 0800 LST) in all three seasons (Fig. 7a). Over YRB-ML, MCS precipitation exhibits an early-morning peak (0700–0900 LST) in summer (Fig. 7b), associated with a strengthened southwesterly low-level jet and an enhanced moisture flux convergence during nighttime to early morning (Chen et al. 2013; Yu et al. 2014; Yu and Li 2016). Spring and autumn feature weaker diurnal variation of MCS precipitation over YRB-ML (Fig. 7b). MCS precipitation over SEC shows two diurnal peaks in spring and summer: one primary peak during nighttime to early morning (0200–0800 LST)

and a secondary peak in the late afternoon (1700–1800 LST) (Fig. 7c). Over LYB, the diurnal cycle of MCS precipitation also exhibits a double peak in summer and has a minimum around noontime (Fig. 7d).

An interesting aspect is the different behavior of the diurnal cycle of non-MCS precipitation (dashed lines) in different seasons. Over YRB-ML and SEC, the diurnal cycle of non-MCS precipitation shows two comparable peaks in spring and autumn (blue and green dashed lines in Figs. 7b,c): one peak is in the nighttime to early morning (0200–0800 LST), which may be due to large-scale weak precipitation (Yu et al. 2014; Yu and Li 2016); the other peak is in the late afternoon (1600–1800 LST), which is mainly produced by frequent and short duration convection due to strong surface heating (Yuan et al. 2010; Yu et al. 2014; Yu and Li 2016). In contrast, the non-MCS precipitation over ETP has only one nighttime peak. The non-MCS precipitation over LYB is weak in spring and autumn (blue and green dashed lines in Figs. 7a and 7d). In summer, non-MCS precipitation (especially the afternoon peak) is enhanced over all subregions (red dashed lines in Figs. 7a–d), due to the monsoonal march and the monsoonal flow providing enhanced moisture (Ding and Chan 2005; Wang 2006; Yu et al. 2014). It should be noted that the “MCS” category used in this study represents long-lived and intense MCSs; other precipitation systems (although some of them also can be well organized, such as light to moderate rainfall associated with the large-scale stratiform clouds of MCSs, smaller-scale MCSs, and shorter-lived MCSs) have been sorted into the “non-MCS” category.

We then check the frequency–intensity structure (Fig. 8) and extremes (Table 1) of MCS precipitation over four subregions in different seasons. The frequency of intense precipitation from MCSs is substantially higher than that from non-MCS precipitation over the ETP, YRB-ML, and LYB (Figs. 8a,b,d) in summer, especially over the ETP in all three seasons (Fig. 8a), indicating that MCSs play a dominant role in contributing to summertime intense precipitation events in aforementioned three subregions. This finding is basically consistent with the results observed over the Great Plains of the United States during warm seasons (Feng et al. 2018). In addition, summertime MCSs have more extremes than those in spring and autumn. There are 185, 193, and 126 h when the maximum hourly precipitation in summer exceeds 50.0 mm h^{-1} over the ETP, YRB-ML, and LYB (Table 1), compared with that of 49 (19), 34 (9), and 0 (10) h in spring (autumn). However, MCS precipitation and non-MCS precipitation over SEC has considerably similar frequency–intensity structure in spring, and non-MCS precipitation is even more intense in summer and autumn in this region (Fig. 8c). Moreover, springtime MCSs over SEC have more extremes (186) than in summer (150) and autumn (14).

The composite of all MCSs at their peak stage over four subregions in different seasons is shown in Fig. 9. The composite figure is an ensemble mean (containing dozens of MCSs in order to indicate the general features of all MCSs; the total number of MCSs over each subregion in different seasons is also shown at upper-right corner of each panel), centered over the individual mass centers of each MCS track at the time of the largest hourly precipitation intensity averaged over its rainfall area. The hourly precipitation intensity of the

FIG. 5. Overall MCS statistical characteristics over four subregions in spring (MAM; blue boxplots), summer (JJA; red boxplots), and autumn (SON; green boxplots): (a) MCS duration (unit: h), (b) MCS rainfall area (unit: 10^2 km^2), (c) MCS average hourly precipitation (unit: mm h^{-1}), and (d) MCS maximum hourly precipitation (unit: mm h^{-1}). In the boxplots, the horizontal bars denote the medium values, the boxes indicate the interquartile range (25th and 75th percentiles), and the whiskers represent 10th- and 90th-percentile values.

composited summertime MCS rainfall center is around $11.0\text{--}13.0 \text{ mm h}^{-1}$ at the peak stage over the ETP, YRB-ML, and SEC (Figs. 9b,e,h), and it can even exceed 14.0 mm h^{-1} over LYB (Fig. 9k). In general, summertime MCSs at the peak phase are more intense than that in spring and autumn (Figs. 9a–c, 9d–f, and 9j–l), except over SEC, where the springtime MCSs have similar precipitation intensity with summertime MCSs at the peak phase (Figs. 9g–i). The core intensity of springtime and autumnal MCSs at the peak phase over LYB is less than 10.0 mm h^{-1} (Figs. 9j,l), but summertime MCSs over LYB can become quite intense at the peak phase ($\geq 14.0 \text{ mm h}^{-1}$; Fig. 9k) because of a warmer condition and adequate moisture due to the monsoonal march (Ding and Chan 2005; Wang 2006; Yu et al. 2014). Summertime MCSs (Fig. 9e) over YRB-ML exhibit a relatively longer and narrower morphology associated with the mei-yu front, which is a subtropical quasi-stationary front with a sharp horizontal low-level wind shear line, and large meridional gradient of moisture and equivalent potential temperature (Chen et al. 2012; Zhou et al. 2018; Guan et al. 2020).

c. The dynamic evolution of the MCS precipitation characteristics as a function of their age

Finally, we investigate the dynamic evolution of the MCS properties (maximum hourly precipitation: Fig. 10; MCS rainfall

area: Fig. 11) in a climatology aspect. It should be noted that Figs. 10 and 11 are also the ensemble mean results, which contain dozens of MCSs in order to describe the general features of the dynamical evolution of MCS precipitation characteristics. There is a rapid intensification in the first 2 h after the MCS genesis, in which the maximum hourly precipitation reaches its peaking phase (Fig. 10); it peaks 2 h before the MCSs reach their largest size (which peaks 4 h after MCS genesis; Fig. 11). The maximum hourly precipitation persists in the next 2–3 h, and then it decreases rapidly (Fig. 10) when the MCS rainfall area becomes smaller (Fig. 11).

There is an obvious regional difference in the dynamic evolution of the MCS properties. MCS rainfall area decreases more quickly over SEC and LYB (Figs. 11c,d), consistent with a bit more rapid decrease of maximum hourly precipitation during the decaying phase over those two subregions (Fig. 10c,d). The springtime MCSs over the ETP have a larger rainfall area, with a higher growth rate of rainfall area during the first 4 h, and they last longer than that of the other three subregions.

In addition, the dynamic evolution of MCS properties exhibits a notable seasonal difference as well. Summer MCSs have notably stronger maximum hourly precipitation during the developing and peak phase in all four subregions (Fig. 10). Spring MCSs have a larger rainfall area during their entire

FIG. 6. Time-longitude Hovmöller diagram (local solar time vs 0.1° longitude bin) of hourly MCS rainfall diurnal variations (unit: mm day^{-1}) (a)–(c) over southern China (for the 21° – 27°N zone) and (d)–(f) along the Yangtze River (for the 27° – 33°N zone) in (a),(d) spring, (b),(e) summer, and (c),(f) autumn. The x axis indicates longitude (unit: $^\circ\text{E}$) and the y axis indicates the local solar time (unit: h).

lifetime (throughout their developing, mature, and decaying stage; Fig. 11). MCSs have similar sizes in summer and autumn (Figs. 11a–c), except for LYB, where autumn MCSs have a larger rainfall area than those in summer (Fig. 11d).

4. Conclusions and discussion

In this study, we have used an iterative rain cell tracking (IRT) method to identify and track long-lived and intense MCSs over eastern China and to investigate the MCS precipitation characteristics and MCS contribution to total rainfall.

Specifically, we have analyzed MCS properties climatologically, including MCS duration, rainfall area, hourly precipitation intensity, and the dynamic evolution of MCS properties, especially focusing on the regional differences and seasonal variations of MCS precipitation characteristics over eastern China.

There are 1085, 2060, and 651 observed MCSs over eastern China in spring, summer, and autumn, respectively, during the study period of 2008–16. Spring MCSs often occur over mountainous areas and contribute up to 45.0% of the total

FIG. 7. Spring (blue lines), summer (red lines), and autumn (green lines) mean diurnal cycle of MCS precipitation (solid lines) and non-MCS precipitation (calculated by using total precipitation minus MCS precipitation; dashed lines) over four subregions (unit: mm day^{-1}): (a) ETP, (b) YRB-ML, (c) SEC, and (d) LYB. The x axis indicates the local solar time (LST; unit: h) and the y axis indicates the MCS and non-MCS precipitation averaged over each subregion (unit: mm day^{-1}).

rainfall in some places of southeastern China (SEC). Spring MCSs also propagate faster compared with those in summer and autumn. In summer, the spatial distribution of MCS precipitation extends northward and covers a wider area [including the lower reaches of the Yellow River basin (LYB)]. Summer also features an additional MCS rainfall center over the eastern Tibetan Plateau (ETP) that contributes up to 50.0% of total rainfall in some parts of that region. In autumn, MCS activity decreases over the whole of eastern China, but MCS precipitation over the ETP is still substantial and accounts for a portion of 20.0%–30.0% to total rainfall.

MCS precipitation over all subregions exhibits a notable seasonal cycle due to monsoon march and retreat. MCS precipitation in SEC begins to increase from March on and has a maximum in June (1.9 mm day^{-1}), contributing to 21.9% of the total rainfall over SEC on average. The lower-to-middle reaches of the Yangtze River basin (YRB-ML) experiences the largest amount and the most pronounced seasonal variations of MCS precipitation among all subregions, exceeding 2.6 mm day^{-1} in June and contributing to over 30.0% of total rainfall from midspring to midsummer. The ETP has most MCS precipitation in June and July, and MCSs persist over the ETP even in September (1.1 mm day^{-1}), contributing 26.7% to the total rainfall. LYB has considerable MCS precipitation only in July and August. Except for these two months, both total rainfall and MCS precipitation remain low over LYB.

Generally, spring MCSs have larger rainfall areas, longer duration, and faster propagation. Summer MCSs have a

stronger precipitation intensity over eastern China, except for SEC, where the spring and summer MCSs have a similar precipitation intensity. MCSs over the ETP have a longer duration than those over other subregions, with 25% of MCSs over the ETP lasting 18 h or longer in spring. Summer MCSs over YRB-ML exhibit a larger size and a relatively longer and narrower morphology, and have a larger propagation speed, associated with the subtropical mei-yu front over this region. Also, summer MCSs rainfall is generally more compactly organized and concentrated over a smaller area, therefore leading to stronger extremes during their developing and peak stages. Spring MCSs rainfall is more widespread throughout the entire lifetime.

Summer MCSs have stronger diurnal variations than those in spring and autumn. They feature a nighttime peak (0300–0400 LST) due to the internal oscillation of the low-level wind, and decrease quickly after sunrise over the ETP. They also exhibit an early-morning peak (0700–0900 LST) over YRB-ML, associated with an enhanced moisture flux convergence. Summer MCS precipitation over SEC and LYB regions exhibits double peaks (with one peak in the nighttime to early morning and the other one in the late afternoon) and has a minimum around noontime.

The frequency of intense summer precipitation from MCSs is substantially higher than that from non-MCS precipitation over almost all of eastern China, indicating that MCSs play a dominant role in contributing to summer intense precipitation events. However, MCS precipitation and

FIG. 8. Frequency distribution of MCS (solid lines) and non-MCS (dashed lines) hourly precipitation intensity in spring (blue lines), summer (red lines), and autumn (green lines) over four subregions: (a) ETP, (b) YRB-ML, (c) SEC, and (d) LYB. The x axis indicates the hourly precipitation intensity (unit: mm h^{-1}) with 1.0 mm h^{-1} bins, and the y axis indicates the frequency (unit: %).

non-MCS precipitation over SEC have a similar frequency–intensity structure in spring, and non-MCS precipitation is even more intense in summer and autumn.

The dynamic evolution of the MCS properties as a function of their age exhibits interesting phenomena. There is a rapid intensification in the first 2 h after genesis, and the peaking time of maximum hourly precipitation is around 2 h before MCSs reach their largest size. The maximum precipitation can persist over the following 2 or 3 h, and then it decreases quickly when the MCSs become smaller. The MCS rainfall area over SEC and LYB decreases more rapidly, consistent with a slightly faster decrease of maximum hourly precipitation during the decaying phase.

MCSs may exhibit different statistical characteristics depending on different chosen variables. For example, tracking MCS by using the precipitation variable will result in shorter MCS duration than tracking MCS by using midtropospheric vorticity or cloud-top properties (Prein et al. 2017a; Feng et al. 2018), because the specific start and end times are sensitive to different chosen variables and different sets of thresholds. Overall, various statistical properties reflect each element of MCSs from different perspectives (Houze 2004,

2018; Yang et al. 2015; Feng et al. 2016, 2018; Prein et al. 2017a,b). In this study, we use the precipitation variable to identify and track MCSs over land regions in China, and the track of an MCS has been ended when it touches the domain boundaries. For future studies, the satellite product will be included to investigate the MCSs characteristics over coastal regions as well as adjacent seas. Also, the identification and tracking method could be improved to consider jointly using two or more combined atmospheric variables (e.g., cloud-top properties and precipitation) when investigating internal structures or cloud microphysics of MCSs over the East Asian monsoon region. Combining the deep convective clouds with intense surface precipitation would give a more relatively comprehensive description of MCS features.

The genesis and development of MCSs over China, as well as associated dynamical and thermodynamical conditions on the synoptic aspect, have been intensively documented in previous studies (Sun et al. 2010; Fu et al. 2011; Chen et al. 2014; Jiang et al. 2014), but revealing the general features of MCSs in a climate perspective to eliminate potential limitations from selected cases is still essential. A comprehensive study of zonal distributions and life cycles of MCSs over China with a special

FIG. 9. Composited average hourly precipitation (within 90.0 km from the MCS rainfall center) of all MCSs at their peak phase (defined as the time when an MCS has the highest hourly precipitation intensity averaged over its rainfall area during the lifetime) in (a),(d),(g),(j) spring (MAM), (b),(e),(h),(k) summer (JJA), and (c),(f),(i),(l) autumn (SON) over four subregions: (a)–(c) ETP, (d)–(f) YRB-ML, (g)–(i) SEC, and (j)–(l) LYB. The x and y axes indicate the relative distances (unit: km) away from the MCS rainfall center. The total number of long-lived and intense MCSs over four subregions in different seasons is shown at upper-right corner of each panel.

focus on the classification of MCSs into different morphologies (e.g., quasi-circular MCSs and elongated MCSs), has been conducted based on brightness temperature data from the geostationary satellite *Fengyun 2* (Yang et al. 2015). Chen et al. (2019) have shown the preliminary results of MCS major features (including horizontal movement and frequency of occurrence) in the whole of East Asia, by investigating a 1-yr-long dataset from Advanced Himawari Imager onboard *Himawari-8*. Other studies have also documented organizational modes (Zheng et al. 2013), life cycle characteristics (Ai et al. 2016), formation mechanisms (Fu et al. 2017) of MCSs, and the associated atmospheric circulation patterns (He et al. 2017) over the plain region of central-eastern China. Cui et al. (2020) have revealed the difference of MCS cloud properties and their associated large-scale environments between southern China and the subtropical mei-yu frontal region. They have found that there is a large interannual variation in MCS

frequency, duration, and precipitation intensity, and indicated that an intensified southwesterly low-level jet and an enhancement of the westerly jet at 500 hPa can provide more favorable conditions for MCS activity. On the basis of previous studies, our work reveals the regional differences and seasonal variations of MCS precipitation characteristics over eastern China during a relatively long time period (from 2008 to 2016). It provides an incremental knowledge on MCSs over the East Asian monsoon region with a focus on the precipitation variable, which is most socially relevant. It should be noted that the long-lived and intense MCS precipitation that we investigate in this study is a subset of total precipitation induced by MCS cloud systems. We do not consider light to moderate rainfall (precipitation intensity below 3.0 mm h^{-1}) related to the large-scale stratiform clouds of MCSs, or shorter-lived MCSs (duration shorter than 6 h).

It is interesting and worthy to note the similarities and differences of MCS properties between eastern China and the

FIG. 10. Development of MCS maximum hourly precipitation as a function of MCS age in spring (blue), summer (red), and autumn (green) over four subregions: (a) ETP, (b) YRB-ML, (c) SEC, and (d) LYB. The shading shows the interquartile spread in each sample, and the solid line shows the medium values. The x axis indicates the MCS age (unit: h) and the y axis indicates MCS maximum hourly precipitation (unit: mm h^{-1}).

central United States, since they both locate downstream of huge mountains and across similar ranges of latitudes. Previous studies have shown that MCSs over the United States exhibit larger size and eccentricity, but with similar durations compared with those over eastern China (Yang et al. 2015). Based on what we have found in this study and conclusions documented in previous studies (Prein et al. 2017a; Houze 2018; Feng et al. 2016, 2018, 2019; Song et al. 2019), we have shown that spring MCSs over eastern China are not that intense and frequent, and account for a smaller proportion of the total rainfall, compared with those of the central United States (Feng et al. 2016, 2019; Song et al. 2019). However, MCSs over eastern China exhibit similar dynamic evolution of the precipitation characteristics, compared with those in the central United States (Prein et al. 2017a; in which the MCSs are also identified and tracked by using precipitation variable, with a similar definition of MCS start time). They also reach the peak in precipitation intensity first, and later reach the largest rainfall area. A similar phenomenon could also be found in a previous study that investigated rainfall events over the Beijing Plain (Yu et al. 2015). In addition, larger MCSs over eastern China also have relatively longer durations. Summer MCS precipitation over the ETP shows diurnal variations similar to those downstream of the Rocky Mountains (Feng et al. 2019),

associated with an enhanced low-level moisture transport during the late night and morning (Chen et al. 2013), but MCS precipitation over YRB-ML exhibits a different diurnal cycle and has an early morning (0700–0900 LST) rainfall peak, consistent with the eastward-delayed phase of the total precipitation in the Yangtze River valley (Chen et al. 2010, 2012). Moreover, a deeper analysis of investigating similarities and differences of MCS properties and associated background circulations over different regions (e.g., eastern China, central United States, and western Africa) is a useful topic of future work, which can deepen our knowledge of the variability of MCS properties on a global scale.

Also, the vertical internal structure of MCSs at different stages (including genesis, developing, mature, and decaying stages) through the lifetime, and the environmental large-scale circulation associated with MCSs over eastern China (especially along the Yangtze River valley) should be investigated in more detail and will be the focus of a separate study. The MCS properties revealed in this study can be applied as the observational metrics to thoroughly evaluate the performance of unified weather and climate models and the forecast skill of seamless prediction systems.

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FIG. 11. As in Fig. 10, but for the development of MCS rainfall area (unit: 10^4 km^2).

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