Characteristics of mesoscale convective systems during the warm season over the Tibetan Plateau based on FY-2 satellite datasets

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Abstract
Mesoscale convective systems (MCSs) often cause heavy precipitation events during the warm season over the Tibetan Plateau (TP). By using the 1-hr gridded data sets with the resolution of 0.1° × 0.1° from the geostationary satellites of Fengyun-2 series (FY-2C/2E), the characteristics of MCSs over the TP during the warm season (May–August) from 2005 to 2012 are analysed. Based on objective criteria, MCSs over the TP can be divided into six categories, namely mesoscale convection complexes (MCCs), persistent elongated convection systems (PECSs), meso-β circular convection systems (MβCCSs), meso-β elongated convection systems (MβECSs), smaller meso-β circular convection systems (SMβCCSs), as well as smaller meso-β elongated convection systems (SMβECSs). The results show that there are 1,465 MCSs occurring over the TP during the warm seasons of 2005–2012, and most MCSs occur in a banded area around 30°N with two high-frequency centres. The frequency of MCSs reaches a maximum in July, followed by August and June, while the lowest frequency occurs in May. The high-frequency centre is located in the northern part of the TP in May, and moves southward to the central and southern part of the TP from June to August. 82.3% of the MCSs over the TP belong to the elongated categories, out of which MβECSs account for the most. MCSs over the TP have significant diurnal variations, which usually initiate at around 1700 LST (LST = UTC + 8 hr), then develop and reach maturity at 2000 LST, then weaken and dissipate at 2200 LST. The life cycles of MCSs are characterized by slow growth and rapid weakening. The larger the scale of MCSs over the TP is, the longer the duration will be.

KEYWORDS
characteristics, FY-2 geostationary satellites, mesoscale convective systems, Tibetan Plateau, warm seasons
INTRODUCTION

The region studied in this paper is the Tibetan Plateau (hereinafter referred to as TP), which refers to the region of 27°N-40°N and 82°E-103°E. It has unique atmospheric circulation, weather and climate characteristics, that are important not only for Asia, but also for the Northern Hemisphere, and even the global weather and climate. Disastrous weather in the lower reaches of the plateau and surrounding areas (hereinafter the central- and eastern China), such as heavy rain, snowstorms, hail, thunderstorms, strong wind and tornadoes, can lead to serious loss of communication and traffic (Wang and Cu, 2011), and is often closely related to the mesoscale convective systems (MCSs). Orlanski (1975) pointed out that MCSs is quite different in scale and shape, sometimes as a mesoscale convective complex (MCC; e.g., Maddox, 1980), sometimes as a persistent elongated convective system (PECS; e.g., Ma et al., 1997; Tao et al., 1998; Zeng et al., 2013).

Some scholars have shown that vertical wind shear, temperature difference and convective available potential energy (CAPE) can affect mesoscale convective systems. For example, an obvious feature of MCC is that the vertical wind shear and CAPE values in the lower troposphere are very large (Laing and Fritsch, 2000). These differences may affect the stratified cloud precipitation and convective precipitation generated by the system, thus affecting the vertical distribution of latent heat release (Houze Jr., 2004). Therefore, a detailed study of the shape of the convective region in MCSs is very important to understand the relationship between MCSs and their environment. In recent years, with the increase of satellite observation data sets, the characteristics of MCSs can be described quantitatively (Houze Jr. et al., 2007; Fu et al.2013). These studies are very useful for understanding the structure of MCSs and its relationship with the circulation background field. Geostationary satellites with high time resolution are usually used to study MCSs (e.g., Zheng et al., 2008; Fu and Wang, 2013). However, most of these studies have focused on mesoscale convective complexes (MCC; Li et al., 1989; Yang and Tao, 2005) or some special types of MCSs, such as MₚCS and MₜCS at meso-α and meso-β scales, respectively. In addition, Zhuo et al. (2012) and Fu and Wang (2013) have studied the category of MCSs in the central- and eastern China. Few studies have focused on the shape of convective regions in MCSs and its relationship with large-scale environments.

Maddox (1980) studied the quasi-circular mesoscale convective system in the central United States using geosynchronous satellite data sets. These satellite images with quasi-circular shape, large area and long duration are often referred to as mesoscale convective complexes (MCC; Table 1). Then many scholars have carried out a lot of research on MCC (Rodgers et al., 1983,Rodgers and Arns, 1985; Tao et al., 1998; Zheng et al., 2008; Jiang and Fan, 2002). Because MCC is a kind of mesoscale convective systems (MCSs), and the characteristics of MCC cannot reflect the characteristics of all MCSs, some scholars have also paid attention to the study of MCSs. Augustine and Howard (1988) cancelled the size requirement that the brightness temperature less than or equal to −32°C must be no less than 10⁵ km², and thought that the threshold of −52°C can fully represent the evolution of MCC (Kane et al., 1987). Many subsequent studies have adopted the modified definition of MCC (Augustine and Howard, 1991; Durkee and Mote, 2010). Another kind of MCSs called persistent elongated convective system (PECS) was discovered by Anderson and Arritt (1998). This type of MCSs is only different from MCC in shape (Table 1). Then, Jirak et al. (2003) further divided the smaller scale MCSs into two types: medium β circular convective system (MβCS) and medium β elongated convective system (MβECS), and divided the whole MCSs into four categories, namely MCC, PECS, MβCS and MβECS (Table 1). In this study, we used four types of MCSs defined by Jirak et al. (2003), and the other two types of MCSs, are small medium β circular convective system (SMβCS) and small medium β elongated convective system (SMβECS), respectively. Their definition standards are similar to those of MβCS and MβECS, except that the cloud cover with infrared brightness temperature

| MCSs category | Area (cold cloud top brightness temperature ≤−52°C) | Duration | Shape (at maximum area) |
|---------------|-----------------------------------------------|----------|------------------------|
| MCC           | ≥50000 km²                                    | Duration ≥6 hr | Eccentricity ≥0.7 |
| PECS          | Same as above                                 | Same as above | 0.2 ≤ eccentricity < 0.7 |
| M₉CSCS        | ≥30000 km² and the largest size ≥50000 km²   | Duration ≥3 hr | Eccentricity ≥0.7 |
| M₉ECS         | Same as above                                 | Same as above | 0.2 ≤ eccentricity < 0.7 |
| SM₉CSCS       | ≥30000 km² and the largest size <50000 km²   | Duration ≥3 hr | Eccentricity ≥0.7 |
| SM₉ECS        | Same as above                                 | Same as above | 0.2 ≤ eccentricity < 0.7 |
less than or equal to \(-52^\circ C\) at the mature moment of the convective system must be less than \(5 \times 10^4 \text{ km}^2\). Table 1 gives a detailed description of the six types of MCSs covered in this paper. Generally speaking, six types of MCSs are divided according to size and shape. MCC and PECS belong to meso-\(\alpha\) scale MCSs (cold cloud area is \(\geq 50,000 \text{ km}^2\)), \(M_p\) CCS and \(M_p\) ECS belong to meso-\(\beta\) scale MCSs (cold cloud area is \(\geq 30,000 \text{ km}^2\)), while SM\(_{\alpha}\) CCS and SM\(_{\alpha}\) ECS belong to Smaller meso-\(\beta\) scale MCSs (cold cloud area is \(>30,000 \text{ km}^2\), the maximum area of cold cloud area is \(<50,000 \text{ km}^2\)). Specifically, in meso-\(\alpha\) scale MCSs, PECS is the ‘linear’ version of MCC, because the only difference between MCC and PECS is the shape of the system. The eccentricity of PECS is between 0.2 and 0.7, while the eccentricity of MCC must be \(\geq 0.7\). In meso-\(\beta\) scale MCSs, \(M_p\) ECS is the ‘linear’ version of \(M_p\) CCS. The eccentricity of \(M_p\) ECS is between 0.2 and 0.7, while the eccentricity of \(M_p\) CCS must be \(\geq 0.7\). Similarly, in Smaller meso-\(\beta\) scale MCSs, SM\(_{\beta}\) ECS is the ‘linear’ version of SM\(_{\beta}\) CCS. The eccentricity of SM\(_{\beta}\) ECS is between 0.2 and 0.7, while the eccentricity of SM\(_{\beta}\) CCS must be \(\geq 0.7\) (Table 1).

In addition, three key moments of initiation, maturity and dissipation are also defined in the life cycle of MCSs. Initiation refers to the moment when the scale definition is first met, maturity refers to the moment when the area of continuous cloud top (the brightness temperature of cold cloud top \(\leq -52^\circ C\)) reaches a maximum size, and dissipation refers to the moment when the scale definition is no longer met (Table 2).

Based on the observation data of Fengyun 2 geostationary satellite (FY-2) for 8 years, the temporal and spatial evolution characteristics of MCSs over the TP are analysed, and the diurnal variation characteristics of MCSs over the TP are mainly studied. It is hoped to provide some reference for the prediction of disastrous weather such as rainstorm and strong convection in this area.

## Table 2

| Definition   | Criterion                                                                 |
|--------------|---------------------------------------------------------------------------|
| Initiation   | The moment when the scale definition is first met                         |
| Maturity     | The moment when the area of continuous cloud top (the brightness temperature of cold cloud top \(\leq -52^\circ C\)) reaches a maximum size |
| Dissipation  | The moment when the scale definition is no longer met                     |
| Life cycle   | From initiation to dissipation. The required duration is \(\geq 3 \text{ hr}\) |

### 2 | DATA AND METHODOLOGY

#### 2.1 | Data

The data of FY-2 series geosynchronous meteorological satellites C, E (hereinafter referred to as FY-2C, FY-2E) used in this paper are provided by the National Satellite Meteorological Center of China Meteorological Administration (CMA). FY-2C and FY-2E products have a temporal resolution of 1 hr and a spatial resolution of 0.1° × 0.1° within the range of 60° S-60°N and 45°E-165°E. This paper focuses on the image data during the warm season (May–August) when the convective systems are relatively active, including FY-2C data sets during 2005–2009, and the rest of the year uses FY-2E data. Figure 1 is the percentage ratio of the year and month satellite data, which is the ratio of the available time of the satellite data to the time of the entire sequence. As can be seen from Figure 1, the average percentage is 96%, and the percentage of FY-2E is more than that of FY-2C, which means that the integrity of FY-2E data are better than that of FY-2C data.

#### 2.2 | Identification and classification methods for MCSs

Generally speaking, the methods of studying MCSs with infrared satellite images are mainly divided into three categories: manual, semi-automated and automated methods. Manual methods refer to the visual inspection of satellite images at first, followed by a subjective...
recognition on the convective systems (e.g., Maddox, 1980; Maddox and Howard, 1982); Automated methods refer to the objective classification for the systems in the infrared images (Carvalho and Jones, 2001; Li et al., 2012); The semi-automated approach, also known as the hybrid approach, typically consists of two steps: first automatically identify the convective cloud cluster, then perform subjective tracking on these systems (e.g., Durkee and Mote, 2010), and then perform a visual check to verify their evolution (e.g., Blamey and Reason, 2012); There is no doubt that the automated approach is the most effective and objective way to classify MCSs. However, the automation approach also has some problems, the most common being the determination that MCSs split and merged as they evolved (Carvalho and Jones, 2001; Durkee and Mote, 2010). Therefore, this paper adopts a semi-automated method similar to Blamey and Reason (2012), which firstly identifies and tracks the system through an automated method, and then carries out visual inspection.

This study mainly adopts the maximum spatial correlation tracking technique (MASCOTTE) method. This method was originally developed by Carvalho and Jones (2001). The main principle is to select and identify cloud features based on the infrared brightness temperature below the predetermined temperature threshold and cloud area above a given size. Systems are then tracked based on the maximum spatial correlation between the target system and all other systems in a consecutive image. Once the system is identified, the method calculates several properties of the convective cloud cluster, such as average cloud top temperature, area of MCSs, eccentricity, and duration of MCSs. This method is used to track MCSs systems in South America (Carvalho and Jones, 2001) and southern Africa (Blamey and Reason, 2012). Through the above methods and followed by the subjective identification with the upper-air and surface weather maps, a data set of MCSs during the warm seasons (May–August) of 2005–2012 within the range of 27°N–40°N and 82°E–103°E is finally obtained. The data set in this study uses the same data set as Yang et al. (2015), but with a smaller range.

3 | RESULTS

3.1 | Spatial distribution

During the eight warm seasons from 2005 to 2012, a total of 1,465 MCSs over the TP are identified and classified (Table 3). Among all the MCSs, 1,205 systems are identified as elongated MCSs (PECS, \( M_\beta \text{ECS} \) and \( SM_\beta \text{ECS} \)) and the rest are quasi-circular MCSs (\( MC_\alpha \text{CCS} \), \( M_\beta \text{CCS} \) and \( SM_\beta \text{CCS} \)), indicating that elongated systems account for more than 82% of the total MCSs. In addition, compared with meso-\( \alpha \)-scale MCSs (MCC and PECS), more systems are classified as the meso-\( \beta \)-scale (\( M_\beta \text{CCS} \), \( M_\beta \text{ECS} \)) and Smaller meso-\( \beta \) scale categories (\( SM_\beta \text{CCS} \), \( SM_\beta \text{ECS} \)), accounting for 65.4 and 20.1%, respectively (a total of 1,252, accounting for 85.5%), while only 213 are classified as meso-\( \alpha \)-scale convective systems (14.5%). Although all types are investigated, meso-\( \beta \) scale and Smaller meso-\( \beta \) scale elongated MCSs are analysed emphatically. The above result is basically consistent with the study results in the central-eastern China (e.g., Zeng et al., 2013), however, the classification of MCSs in the lower Yellow River in China is slightly different from previous studies (e.g., Zhuo et al., 2012).

Figure 2b shows the initial locations of all MCSs during the 8-year period. It can be seen that in the study area of (27°N–40°N, 82°E–103°E), MCSs mainly occur in a zonal-banded region around 30°N with two high-frequency centres. The initial locations of the zonal region with MCSs may be related to topographic features. This zonal region is mainly located in the south-central part of the TP and extends eastwards to the central-eastern China. Meanwhile, it is located on the northern side of the Himalayas, and two high-frequency centres in the south-central part of the plateau and in the Hengduan Mountain (Figure 2a) southeast of the plateau have been also observed (Figure 2b). The overall spatial distribution of MCSs over the TP is characterized by one band and two centres, that is to say, the MCSs over the TP is generally distributed in a band, and there are two large value centres on the east and west sides (Figure 2b). This is basically consistent with the results of Fu and Wang (2013).

| Type | Meso-\( \alpha \) scale MCSs | Meso-\( \beta \) scale MCSs | Smaller meso-\( \beta \) scale MCSs | Total |
|------|-----------------------------|-----------------------------|----------------------------------|-------|
| Quantity | 213 | 957 | 295 | 1,465 |
| Quantity | MCC | PECS | \( M_\beta \text{CCS} \) | \( M_\beta \text{ECS} \) | \( SM_\beta \text{CCS} \) | \( SM_\beta \text{ECS} \) | Total |
| Quantity | 19 | 194 | 168 | 789 | 73 | 222 | 1,465 |
From Figure 3, we can see the spatial distribution of the initial positions of six category of MCSs. Although the high-frequency centres of six-category MCSs shown in Figure 3 are similar to those in Figure 2b, different categories of MCSs tend to cluster in their own occurrence-prone areas. For example, the occurrence number of quasi-circular MCSs is relatively small in the vicinity of a banded region within 30°N–32°N (Figure 3a). The high-frequency centres of these quasi-circular MCSs are mainly distributed in the southern part of the plateau; More specifically, the high frequency centre of the initial MβCCS usually occurs in the southeast of the plateau. While SMβCCSs and MβCCSs occur relatively more frequently on the northern slope of the Himalayas. Compared with the quasi-circular MCSs, the elongated systems account for the majority of the total MCSs, and they are distributed in almost the entire zonal regions (Figure 3b,d,f). For PECS and MβECS, the high frequency centre usually appears on the northern slope of the Himalayas and the southeast of TP, respectively, while SMβECSs appear in both regions, with a relatively lower frequency. More specifically, few MCCs have been observed over the TP, and the main type of MCSs in this area is the MβECS (Figure 3d).

As can be seen from Figure 4, the spatial frequency distribution of MCSs in the study area, including total MCSs, different-size (meso-α, meso-β and smaller meso-βsized) MCSs and different-shape (quasi-circular and elongated) MCSs. It can be seen from Figure 4 that although the high frequency centre of MCSs is similar to that in Figure 2b, but different categories of MCSs still present different characteristics. On the whole, the spatial distributions of the three-type (meso-α, meso-β and smaller meso-βsized, Figure 4b–d) MCSs are basically the same, which zonally distribute along 30°N from west to east, but the high-frequency centres of MCSs with different sizes and shapes are located slightly different. For example, the high-frequency centres of meso-osized MCSs are mainly located in the regions south of the Himalayas (Figure 4b). More specifically, over the plateau, the frequency of the initial MCCs is relatively lower, while that of initial PECSs is the highest with the centre around (30°N, 87°E). Unlike meso-osized ones, meso-βsized systems, which account for the majority of the total MCSs, almost distribute in the entire zonal region of 28°N–34°N (Figure 4c), with the highest-frequency centres located around (29°N, 86°E) and (30°N, 100°E), respectively. In addition, the spatial distribution of smaller meso-β sized MCSs is similar to that of meso-osized MCSs, and the two high-frequency centres are located at (29°N, 91°E) and (27°N, 101°E) in the Hengduan Mountains, respectively. On the other hand, the meso-β-scale convective systems obviously dominate in the latitude zone of the plateau. In the data sets of MCSs, very few MCCs are observed over the plateau (Figure 3a), and the main type of MCSs in this area is the MβECS (Figure 3d). These meso-β sized systems observed over the plateau are likely to be related to the steep topography and topographical uplift, leading to the rapid formation and further splitting of MCSs (Jiang and
Fan, 2002; Yang and Tao, 2005), as well as the formation of meso-β sized MCSs finally.

Figure 4e shows that the elongated MCSs at the initial moment basically present a zonal distribution, with the highest-frequency centre located near (30°N, 87°E). In addition, there are several smaller centres in the eastern part of the plateau. On the other hand, compared with elongated MCSs, there are relatively fewer quasi-circular MCSs (Figure 4f), with the high-frequency centre located near (30°N, 100°E) in the areas of Hengduan Mountains.

3.2 Inter-annual and monthly variations

During the eight warm seasons (May–August) from 2005 to 2012, it can be seen that the average number of MCSs per year in the study area is about 183, while the maximum and minimum number of MCSs reach 289 and 134, respectively (Figure 5). The peak of MCSs (289) appears in 2010, followed by 192 in 2005, that is, 481 MCSs in total. With regard to the monthly variation, the number of MCSs ranges from a minimum of 108 to a maximum of 658, with an average value of 366 (Figure 5). The peak of MCSs appears in July, then the MCSs number decreases gradually in August and June, and it reaches a valley in May. In addition, the M_β ECS accounts for the largest proportion at both inter-annual and monthly scales.

In addition to the monthly variation of total MCSs, the spatial distribution of MCSs also changes significantly month by month. Figure 6 shows the spatial distributions for the initial MCSs from May to August. It can be seen that there are three main features: the overall stable location with little movement, the rapid increase in the number of MCSs and several areas with high-frequency MCSs.

The first feature is that the initial locations of MCSs month by month are generally characterized by an
overall stability and less movement. In May, the initial locations of MCSs are mainly located in the central and northern part of the TP (Figure 6a). When it comes to June, the high-frequency centre of MCSs moves southward to the south-central part of the TP (Figure 6b). While in July, the overall location changes little, and large-value centres appear in the south-central part of the plateau and near the Hengduan Mountains (Figure 6c). And the situation in August is similar to that in July overall, with a slight decrease in the frequency (Figure 6d). The main reason for the stability is that when the East Asian summer monsoon (EASM) began to break out, the southerly and southwesterly winds outside the subtropical high brought warm and humid tropical air (Ding and Chan, 2005; Xu and Zipser, 2011), creating good environmental conditions for the occurrence of MCSs.

The second feature is the rapid increase in the number of MCS activities observed over the TP during the warm season (May–August). It can be seen that there is a small amount of MCSs over the northern TP in May (Figure 6a). In June, the MCSs obviously move southward, with a large-value centre in the south-central part of the plateau (Figure 6b). However, the MCS activities over the plateau increase rapidly in July, which are mainly located on the northern slope of the Himalayas and near the Hengduan Mountains (Figure 6c). In August, the total number of MCSs gradually decreases, and the large-value centre is mainly located on the northern slope of the Himalayas (Figure 6d). Studies on the increase of extreme convections over the plateau during the monsoon season have demonstrated that westerly wind and high relative humidity may contribute to the formation of MCSs in this region (Romatschke
et al., 2010; Qie et al., 2014). During the monsoon season, the westerly wind gradually weakens from May to August, while the relative humidity in the eastern part of the TP increases. Subsequently, the intense heating from the TP leads to the thermal low pressure in the near-surface layer and a corresponding high pressure in the middle and upper troposphere, which intensifies the ascending motion caused by the plateau, especially during June–July. Therefore, the frequency increase of MCSs can be explained by the ascending motion caused by topographic forcing and the increase of water vapour content in the atmosphere. On the other hand, the decrease in August is related to the variation of the summer monsoon circulation. However, further researches are needed to correctly identify possible causes (Houze Jr. et al., 2007; Xu and Zipser, 2011; Qie et al., 2014).

The third feature is the existence of several regions with high-frequency MCSs, indicating that there are regions with continuous MCSs activities over the TP during the warm season, which are mainly located in the south-central part of the TP (i.e., the northern slope of the Himalayas) and near the Hengduan Mountains (Figure 6c,d).

Figure 7 shows the monthly variation of the total numbers of six-category MCSs during eight warm seasons. As can be seen from the figure, the elongated system shows more significant monthly variation than the
quasi-circular system (Figure 7d–f). The frequency of elongated MCSs increases from May to July, and then decreases slightly in August, while MβCCSs and SMβCCSs also show similar characteristics to elongated systems (Figure 7b,c). As the number of MCCs is relatively small, there is no significant monthly variation, except that a minimum occurrence frequency of MCCs appears in May (Figure 7a).

3.3 Characteristics of diurnal variations

Figure 8 shows the diurnal variation characteristics (diurnal cycle) of MCSs at three key moments of the life cycle (initiation, maturity and dissipation). It can be seen that the initiation, maturity and dissipation of MCSs may occur at any time of the day, but the occurrence frequency at each moment shows an obvious diurnal variation. The initiation of MCSs with the high frequency occurs during afternoon to evening, and lasts for about 6 hr, mostly from 1,500 to 2,100 LST. More specifically, the frequency of the initial state of MCSs begins to increase at about 1,500 LST and keeps increasing for the next 3 hr, reaching its peak at 1,700 LST, and then subsequently decreases gradually in the next 4 hr. The diurnal variation for the maturity of MCSs has some similar characteristics to that for the initiation, that is to say, the high frequency for the maturity of MCSs also lasts for nearly 6 hr, and the peak frequency mainly appears between 1,700 and 2,300 LST. The diurnal variation for the dissipation of MCSs also has some similar characteristics to that for the initiation, that is, the high frequency for the dissipation lasts for nearly 6 hr, and the peak frequency mainly occurs between 2,000 and 0100 LST. The frequency at two moments (maturity and dissipation) gradually increases in the first 3 hr of the high-frequency periods, and then decreases in the last 3 hr of the high-frequency periods. It can be seen that the highest frequencies for the initiation, maturity and dissipation appear at 1,700, 2,000 and 2,200 LST, respectively, indicating that the peak frequency for the maturity (dissipation) occurs only 3 hr after that for the initiation (maturity) of MCSs. However, there is a certain difference in the peak numbers of MCSs at each key moment—the number of MCSs at the initiation
(maturity) moment is more than that at the maturity (dissipation) moment, indicating that the frequency of MCSs in the initial period is higher than that in the other two periods. On the other hand, there is a secondary peak from 0000 to 0400 LST. It can be seen that the secondary peaks for the initiation, maturity and dissipation appear at 0100, 0200 and 0300 LST, respectively.

Although different categories of MCSs show similar diurnal cycles of the frequencies at the three moments, there are certain unique characteristics for some categories, especially for quasi-circular systems (Figure 9). For example, the initiation of MCCs averagely reaches its peak between 1,600 and 1800 LST, while the peak for the maturity of MCCs arrives about 3 hr later than the initiation, that is, between 2,000 and 2,200 LST. The dissipation of MCCs mainly occurs between 2,200 and 0200 LST, almost 3 hr later than the peak frequency of the maturity (Figure 9a). For MβCCSs, the high frequencies for the initiation and maturity occur during 1,600–1,800 LST and 1,900–2,200 LST respectively, but the peak of the maturity is 1 hr later than that observed for the total MCSs (Figure 9c). For SMβCCSs, the high-frequency periods for the three moments overlap more obviously than those of the other two quasi-circular systems (MCC and MβCCS). The high frequency for the initiation reaches its peak at 2,000 LST, while that for the maturity and dissipation occurs at 1,900 and 2,300 LST, respectively, and both the latter two reach the peak at 2,200 LST (Figure 9e). At the same time, SMβCCSs show secondary peaks at 0200, 0500 and 0600 LST for the frequencies of the initiation, maturity and dissipation, respectively (Figure 9e). Compared with the quasi-circular systems, the elongated MCSs have a more similar diurnal cycle to the total MCSs, and the

![Figure 8](image-url) F I G U R E 8  Frequencies of all MCSs at the moments of initiation, maturity and dissipation during the life cycle

![Figure 9](image-url) F I G U R E 9  Frequencies of six-category MCSs at the moments of initiation, maturity and dissipation: (a) MCC, (b) PECS, (c) MβCCS, (d) MβECS, (e) SMβCCS and (f) SMβECS
peak is more probably to appear from noon to the first half night at each moment, specifically referring to 1,500–2,400 LST. For example, the high-frequency periods for \( M_{\beta}ECS \)s at the three key moments are 1,600–1,900 LST, 1,800–2,200 LST and 2,000–2,400 LST, respectively (Figure 9d); and the peaks appear at 1,700, 2,000 and 2,200 LST, respectively, which is basically consistent with the diurnal variation of the total MCSs.

In a word, MCSs over the TP usually initiate at about 1,700 LST in the afternoon, mature around 2,000 LST in the evening, and tend to dissipate around 2,200 LST. This diurnal cycle is mainly affected by the diurnal variation of solar radiation, which has already been confirmed in previous studies in this region (Zheng et al., 2008; Xu and Zipser, 2011; Li et al., 2012) and in other parts of the world (e.g., Carvalho and Silva Dias, 2002; Nesbitt and Zipser, 2003; Romatschke et al., 2010; Blamey and Reason, 2012). Studies by Xu and Zipser (2011) have shown that the maximum nocturnal precipitation occurs in the foothills of the southeastern TP, due to the inflow of moist air in the lower layers at night, probably contributing to the formation and maintenance of nocturnal activities in the foothills of Himalayas.

### 3.4 Important characteristic quantities

The average duration of the 1,465 MCSs in the study area (TP) is 7.2 hr (Table 4), which is slightly longer than that in the central- eastern China (~6.6 hr; Zeng et al., 2013), but much shorter than that in the lower reaches of the Yellow River (10.0 hr; Zhuo et al., 2012). Figure 10 shows the histogram for the durations of MCSs. It shows that the total number of MCSs decreases with the increase of duration in systems of both \( \alpha \)- and \( \beta \)-scale. More than 72% of the MCSs have a lifetime of 3–6 hr, and according to the duration requirement defined in Section 2, the number of MCSs reaches a peak in the first 3 hr at both \( \alpha \)- and \( \beta \)-scale. More specifically, \( SM_{\beta}CCS \)s and \( SM_{\beta}ECS \)s have the largest number for the duration of 3–6 hr, fewer of them show the duration of 6–9 hr, while almost none of them show the duration of 9–12 hr. It indicates that these two systems exhibit the longest lifetime of 9 hr, which rarely last for 9–12 hr, and basically none of them could last more than 12 hr. The number of \( M_{\beta}CCS \)s and \( M_{\beta}ECS \)s with the duration of 3–6 hr is almost the same as that with the duration of 6–9 hr, while the number of the two-category systems with the duration of 9–12 hr decreases significantly and keep decreasing for more than 24 hr. Moreover, the number of the two-category decreases rapidly with the increase of duration. In addition, most of the systems with the duration of more than 9 hr are the \( M_{\beta}ECS \) and \( M_{\beta}CCS \), some of which even last for more than 24 hr, indicating that the lifetime of these two-category systems is very long. Similar to the \( \beta \)-scale systems, the number of MCCs and PECSs reaches the

![Figure 10](image-url) Histogram for the duration of MCSs during the warm season (unit: hour)

### Table 4

| Type        | Maximum area \((10^4 \text{ km}^2)\) | Duration (hr) | Eccentricity | Average TBB (°C) | Lowest TBB (°C) |
|-------------|-------------------------------------|---------------|--------------|------------------|-----------------|
| MCC         | 14.0                                | 10.3          | 0.78         | −61.9            | −68.0           |
| PECS        | 15.3                                | 9.2           | 0.44         | −61.0            | −71.0           |
| \( M_{\beta}CCS \) | 10.1                         | 8             | 0.78         | −61.4            | −71.0           |
| \( M_{\beta}ECS \) | 11.3                         | 7.5           | 0.46         | −60.8            | −81.0           |
| \( SM_{\beta}CCS \) | 4.2                          | 7.5           | 0.79         | −61.1            | −73.0           |
| \( SM_{\beta}ECS \) | 4.2                          | 4             | 0.50         | −60.6            | −81.0           |
| ALL MCSs    | 9.8                                 | 7.2           | 0.63         | −61.1            | −74.2           |
peak when the duration is between 6 and 12 hr, and it decreases for the duration of 12–15 hr, followed by a sharp decrease for the duration of 15–18 hr, and subsequently disappears for the duration of 18–21 hr (Figure 10).

Figure 11 shows the distribution for the maximum area of MCSs at the maturity moment. Two categories of SM\textsubscript{\textbeta}CCS and SM\textsubscript{\textbeta}ECS, whose area is within the range of $3 \times 10^4 – 5 \times 10^4$ km\textsuperscript{2}, are excluded. It can be seen that negative correlations exist between the frequency of MCSs and the corresponding maximum area at the maturity moment (e.g., Jirak \textit{et al}., 2003). The frequency of MCSs accounts for the most when the corresponding maximum area is within the range of $5 \times 10^4 – 8 \times 10^4$ km\textsuperscript{2}, and these systems are mainly the M\textsubscript{\textbeta}CCS and M\textsubscript{\textbeta}ECS. The number of MCCs and PECSs is gradually increasing when the maximum area ranges from $8 \times 10^4$ to $1.4 \times 10^5$ km\textsuperscript{2}, while the number of M\textsubscript{\textbeta}CCSs and M\textsubscript{\textbeta}ECSs decreases. For the average maximum area within the range of $1.4 \times 10^5 – 3.5 \times 10^5$ km\textsuperscript{2}, frequencies of all-category MCSs decrease with the increase of area. In addition, the maximum area of \textalpha{}- and \textbeta{}-scale systems (MCC, PECS and M\textsubscript{\textbeta}CCS, M\textsubscript{\textbeta}ECS) all exceeds $3.5 \times 10^5$ km\textsuperscript{2}. From the average value of the important characteristic quantities (parameters) for each-category MCSs (Table 4), it can be seen that the mean maximum area of all MCSs is $9.8 \times 10^4$ km\textsuperscript{2}, which is slightly larger than that in the previous study ($9.5328 \times 10^4$ km\textsuperscript{2}, Zeng \textit{et al}., 2013). In addition, the average maximum area of PECSs has the largest value (larger than $1.53 \times 10^5$ km\textsuperscript{2}), while that of smaller meso-\textbeta{}sized systems is about $4.2 \times 10^4$ km\textsuperscript{2}. In accordance with the duration criteria discussed earlier, the average duration of these meso-\textbeta{}sized systems (9–10 hr) is longer than that of smaller meso-\textbeta{}sized systems (about 4 hr) (Table 4). It can be seen from Table 4 that the size of the system is positively correlated with the duration. For example, the duration of the meso-\textbeta{} scale MCSs (M\textsubscript{\textbeta}CCS and M\textsubscript{\textbeta}ECS) is longer than the Smaller meso-\textbeta{} scale MCSs (SM\textsubscript{\textbeta}CCS and SM\textsubscript{\textbeta}ECS) (Table 4). Similarly, the quasi-circular system has a slightly longer duration than the elongated system. For example, the duration of the M\textsubscript{\textbeta}CCS is longer than the M\textsubscript{\textbeta}ECS (Table 4). It can be seen that the average eccentricity is almost the same (0.78) for all the quasi-circular systems, while it ranges between 0.44 and 0.50 for the three types of elongated systems (Table 4).

From Figure 12, it can be seen that the eccentricity of MCSs at the maturity moment generally presents a normal distribution. The peak for the eccentricity of MCSs occurs between 0.40 and 0.55 (accounting for about 32%), indicating that most systems at the maturity moment are elongated MCSs (accounting for about 82%). For the quasi-circular systems (accounting for about 17.8%), the peak eccentricity at the maturity moment is between 0.70 and 0.80. Moreover, with the increase of eccentricity, the number of three-category quasi-circular MCSs shows an obvious decreasing trend, indicating that the number of MCSs is less when the shape is more close to the circular shape.
Another property for MCSs is the average cloud-top infrared brightness temperature (hereinafter referred to as the average cloud-top brightness temperature). The average cloud-top brightness temperatures of the six-category MCSs are $-61.9^\circ$C (MCC), $-61^\circ$C (PECS), $-61.4^\circ$C (M$\beta$CCS), $-60.8^\circ$C (M$\beta$ECS), $-61.1^\circ$C (SM$\beta$CCS) and $-60.6^\circ$C (SM$\beta$ECS), respectively. It is also shown that the average cloud-top brightness temperature of $\alpha$-scale ($\beta$-scale) systems is about $-61.5^\circ$C ($-61.1^\circ$C). The average cloud-top brightness temperatures of MCSs at $\alpha$- and $\beta$-scale show minimum values of $-69.5$ and $-76^\circ$C, respectively, while that of M$\beta$ECSs and SM$\beta$ECSs is the lowest ($-81^\circ$C) (Table 4).

4  |  SUMMARY AND DISCUSSION

The TP is often affected by heavy rainfall caused by frequent MCSs. In recent decades, many studies have focused on the characteristics and environmental physical fields of MCSs. Using high-density infrared satellite images to study the MCSs over the TP is helpful for us to understand the climatic characteristics of MCSs in this area, and then to understand the temporal and spatial distribution of heavy precipitation and strong convection. MCSs are divided into six categories: MCC, PECS, M$\beta$CCS, M$\beta$ECS, SM$\beta$CCS and SM$\beta$ECS, which are further analysed to explore the differences of spatio-temporal and shape characteristics among all the categories.

During the warm season from 2005 to 2012, a total of 1,465 MCSs were identified over the TP. About 82% of all MCSs are elongated systems, out of which M$\beta$ECSs account for the most. The spatial distributions of the three-type MCSs (meso-$\alpha$-sized, meso-$\beta$-sized and smaller meso-$\beta$-sized) are basically the same—a zonal distribution along 30°N from west to east, but the high-frequency centres of MCSs with different sizes and shapes are slightly different, that is to say, there is a clear relationship between MCSs categories and geographical location. For example, most of the MCSs over the TP are M$\beta$ECS, high frequency centres located on the northern slope of the Himalayas and near the Hengduan Mountains. The complex topography and the characteristics of the underlying surface may play a role in the difference of MCSs distribution.

The monthly frequency of MCSs reaches a maximum in July, followed by August and June, while the minimum appears in May. In addition, the spatial distributions of MCSs month by month reveal a small amount of MCSs in the northern TP in May and an obviously southward moving of their location in June, with large-value centres in the south of the central plateau. The frequency of MCS activities over the plateau increases rapidly to a peak in July, and the total number of MCSs decreases significantly in August. The high-frequency centres of MCSs are mainly located on the northern slope of the Himalayas and near the Hengduan mountains.

The average lifetime of MCSs over the TP is 7.2 hr, while it is about 10 hr for MCC and PECS, 8 hr for M$\beta$CCS and M$\beta$ECS, 4 hr for SM$\beta$CCS and SM$\beta$ECS. The average maximum area of MCSs is $9.84 \times 10^4$ km$^2$. The maximum area of most MCSs ranges from $5 \times 10^4$ km$^2$ to $8 \times 10^4$ km$^2$. In addition, the shape of the system is independent of its duration and size. That is to say, the average eccentricity of $\alpha$-scale (elongated and quasi-circular) MCSs is almost the same as that of $\beta$-scale (elongated and quasi-circular) MCSs. The eccentricity of most MCSs is between 0.40 and 0.55 (about 32%), indicating that elongated MCSs account for the vast majority of the total MCSs. Besides, MCSs over the TP have significant diurnal variations, which usually initiate at about 1,700 LST, followed by a developing, and mature at 2,000 LST, then after the weakening period, finally dissipate at 2,200 LST. It can be seen that in the life cycle of MCSs, the enhancing moment is longer than the weakening moment.

This study is helpful to understand the spatial distribution and temporal evolution of MCSs over the TP, and these analyses can be used for the follow-up study of the relationship between MCSs and their environment. Future work will focus on the synoptic and mesoscale features that are very important in the initiation and evolution of these different types of MCSs.

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