A Statistical Analysis of Hail Events and Their Environmental Conditions in China during 2008–15

MINGXIN LI
State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China

DA-LIN ZHANG
State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China, and Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, Maryland

JISONG SUN
State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China

QINGHONG ZHANG
Department of Atmospheric and Oceanic Sciences, Peking University, Beijing, China

(Manuscript received 20 April 2018, in final form 23 October 2018)

ABSTRACT

An 8-yr (i.e., 2008–15) climatology of the spatiotemporal characteristics of hail events in China and their associated environmental conditions are examined using hail observations, L-band rawinsondes, and global reanalysis data. A total of 1003 hail events with maximum hail diameter (MHD) of greater than 5 mm are selected and then sorted into three hail-size bins. Hail events with the largest MHD bin correspond to the median vertical wind shear in the lowest 6-km layer (SHR6) of 21.6 m s\(^{-1}\), precipitable water (PW) of 34.8 mm, and convective available potential energy (CAPE) of 2192 J kg\(^{-1}\). Hail with different MHD bins share similar freezing-level heights (FLHs) of about 4000 m. The thickness of the hail growth zone is thinner for hail events with the largest MHD bin. Hail events with different MHD bins display seasonal variations associated with the summer monsoon; that is, the hail season starts in South China in spring and then shifts to North China in summer. Larger hail is mainly observed during the spring in South China before monsoon onset in the presence of an upper-level jet and a low-level southwesterly flow accounting for large SHR6 and PW. In contrast, smaller-MHD hailstorms occur mainly during the summer in North China when surface heating is high and the low-level southerly flow shifts northward with pronounced baroclinicity providing large CAPE and PW, moderate SHR6, and low FLH. Environmental CAPE and SHR6 for large hailstones in China are comparable in magnitude to those in the United States but larger than those in some European countries.

1. Introduction

A recent cloud–hail modeling study of Brimelow et al. (2017) indicates that while hail days are projected to decrease over southern North America and increase over the central to northern plains during spring and summer, the mean hail size is projected to increase under a warming climate background. The observational studies of Tippett et al. (2015) and Allen and Tippett (2015) reveal that under a warming climate, large-hail days stay unchanged but small-hail days tend to increase due to changes in the reporting system in the United States during 1955–2014. On the other hand, Ni et al. (2017) find that hail-size spectra have shifted toward smaller sizes over the past 35 years, based on continuous and coherent hail-size records from 2254 manned stations across China. Li et al. (2018) note that hailstones larger than 20 mm in diameter, accounting for 5.32% of all hail reports, are less frequently observed in China than in the United States. Hail sizes and size changes across China also differ from those occurring in the United States. Given their similar latitudinal

Corresponding author: Dr. Da-Lin Zhang, dalin@umd.edu

DOI: 10.1175/JAMC-D-18-0109.1

© 2018 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
dispositions, could the above differences be attributed to different environments in which the associated hailstorms are embedded between the two countries?

Before addressing the above question, it is necessary to understand the factors influencing hail size. As hail formation is typically tied to more intense and long-lived thunderstorms, as represented by strong updrafts and vertical wind shear (VWS) (Nelson 1983, 1987; Ziegler et al. 1983; Dennis and Kumjian 2017; Allen 2017), numerous studies have been performed to investigate the impact of environmental convective available potential energy (CAPE) and VWS in the lowest 6-km layer (SHR6) (Johnson and Sugden 2014; Tuovinen et al. 2015; Dennis and Kumjian 2017). Although the magnitudes of CAPE and SHR6 for hail formation vary from region to region (e.g., 1464 J kg$^{-1}$ and 17.5 m s$^{-1}$ for severe hailstorms in Finland but much greater values in the United States), all previous studies show that large hailstones tend to develop in an environment with moderate to large CAPE and strong SHR6. In addition, the melting effect represented by the freezing-level height (FLH) is of great significance, especially for small hailstones (Xie et al. 2008, 2010; Tippett et al. 2015; Mahoney et al. 2012; Li et al. 2016; Brimelow et al. 2017). The frequency of hail occurrence has been shown to be closely related to moisture transport in North China; namely, reduced moisture transport decreases frequency (Li et al. 2016). Some studies indicate that hailstorms tend to develop in relatively dry environments (e.g., Zheng et al. 2013). In particular, many previous studies in China have been dedicated to understanding why the hail-occurrence frequency has decreased dramatically over the past few decades by examining changes in some environmental parameters (e.g., Xie et al. 2008; Li et al. 2016). However, most of the previous studies did not consider the environments in which hailstorms were actually developing, and few studies have been performed to systematically examine the proximity environmental conditions of hail events over China. Clearly, studying the proximity conditions, in which hailstorms producing different hail sizes are embedded, would help improve our understanding of hail-favorable environments as well as the long-term trend of hail-occurrence frequency.

Previous studies show large monthly variations in hailstorms across the United States; that is, hail is first observed in early spring in the southern United States and occurrences peak in May and June in the southern plains; then hail threats drift northward to the central and northern plains during July and August, before diminishing in the fall (Doswell et al. 2005; Allen et al. 2015; Cintineo et al. 2012; Cecil and Blankenship 2012). Allen et al. (2015) developed an empirical model of the annual cycle of hail occurrences and their spatial distribution over the United States, in which the annual cycle is determined by the following four environmental parameters: convective precipitation, CAPE, relative helicity, and mean specific humidity in the lowest 100-hPa layer. Cecil and Blankenship (2012) examined a global climatology of severe hailstorms using satellite passive microwave imagers. They find that hailstorms over most continental regions reach their peak in late spring or early summer, and that the South Asian monsoon alters the hailstorm seasonal cycle over the Indian subcontinent. Among these studies, comparatively few have investigated the seasonality of hail-related environments.

Hail climatology in China has also been extensively studied over the past few decades (Liu and Tang 1966; Zhang et al. 2008; Xie et al. 2008; Li et al. 2016). A recent study of hail occurrences and hail sizes by Li et al. (2018), using hail observations from 2254 meteorological stations, shows that hailstorms peak in June in North China and across the Qinghai–Tibet Plateau, whereas over South China both hail-occurrence frequencies and severe hailstorms (i.e., with hail larger than 20 mm in diameter) peak in late spring. Despite many hail climatological studies in China, few have examined the large-scale circulation patterns and environmental conditions, in which convective storms generating different hail sizes are embedded. Thus, the objectives of this study are to (i) examine what hail-favorable environments in China are, and how they differ from those in other geographical locations; and (ii) explore how the hail-favorable proximity environmental conditions are related to the seasonal cycle of large-scale flows. The above objectives will be achieved by analyzing hail records, including both hail-occurrence frequencies and maximum sizes, from more than 2000 surface stations and the L-band radar digital rawinsonde data that were archived during the period of 2008–15.

The next section introduces the datasets and methodology used for the present study. Section 3 shows the spatiotemporal characteristics of hail events, and the proximity environmental conditions and synoptic circulations in which hailstorms with different MHDs are embedded. Section 4 discusses the influences of the East Asian summer monsoon (EASM) on the shift of hailstorms in China, as well as some hail diameter differences obtained between China and the United States. A summary and concluding remarks are given in the final section.

2. Data and methodology

Hail observations used for this study are archived by the National Meteorological Information Center
(NMIC) of the China Meteorological Administration (CMA); the dataset includes complete records of hail events with different MHDs and the times of hail occurrences from 2477 stations throughout mainland China during the period from 1954 to 2015. Twice-daily [i.e., 0800 and 2000 Beijing standard time (BST = UTC + 8 h)] L-band rawinsondes with high quality moisture measurements providing observations every minute (Zhang et al. 2007) are used to examine hail-favorable environments. Whenever necessary, the rawinsondes are modified, based on the 6-hourly surface winds, temperature, and dewpoint temperature at the closest surface stations prior to the hail report time, in an attempt to yield a well-mixed planetary boundary layer (PBL) during the late afternoon hours for the purpose of estimating the lifting condensation level and SHR6. Because the L-band rawinsondes are only available since 2008, we performed an analysis of hail climatology during the 8-yr period of 2008–15.

In this study, a hail event is defined when a hailstorm is recorded at one station on a specific day. Hail events are selected from the years of 2008–15, if there is at least one upper-air sounding within a 100-km distance from the hail report station on that day. The sounding closest to the hail report is used if more than one are available. Hail reports with MHDs smaller than 5 mm are excluded. As a result, a total of 1182 hail events are found and then sorted into three size bins: 5 \( \leq \) MHD < 10 mm, 10 \( \leq \) MHD < 30 mm, and MHD \( \geq \) 30 mm, hereafter referred to as the MHDs of D1, D2, and D3, respectively. As no unified hail-size threshold has been used for hail events occurring over different countries, the MHD thresholds of 5, 10, and 30 mm are selected herein to better differentiate the environmental parameters of different hail-size bins. Figure 1 shows the distribution of the 1182 hail events with different colors representing the three size bins, as well as the 117 rawinsonde stations as marked by plus signs. Because of the sparse population and limited meteorological stations in West China, we will focus more on hail events in the eastern portion of China (i.e., east of line A and south of line B as indicated in Fig. 1). This portion is referred hereafter to as the study area, which accounts for 1003 hail events out of the 1182 total events.

Among the multiple sounding-derived parameters, CAPE, SHR6, precipitable water (PW), FLH, and the thickness of hail growth zone (HGZ), are used to determine the hail-favorable environmental conditions. CAPE refers herein to the most unstable parcel (i.e., for the most unstable air parcel in the lowest 300-hPa layers), and it is calculated by vertically integrating the thermal buoyancy from the level of free convection to the equilibrium level. SHR6 is defined as the magnitude of the VWS vectors between the surface and 6-km altitude. Note that SHR6 is selected here, instead of helicity, and includes both vertical speed and directional shears (Allen et al. 2015), in order to better compare this work to some of the previous studies. The moisture supply is described by PW that is obtained by integrating specific humidity from the surface to 100 hPa. FLH is the height above which the air temperature is below 0°C. HGZ is defined as the layer bounded by \(-10^\circ\) and \(-30^\circ\) (Nelson 1983; Foote 1984; Miller et al. 1988; Knight and Knight 2001; Johnson and Sugden 2014). Parameter differences between the size bins D1, D2, and D3 were tested with the Mann–Whitney rank sum method (Wilks 2011).

Since almost all hail events under study occur during the afternoon hours, data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis-2, with 2.5° horizontal resolution at 1400 BST during 2008–15, are used to calculate CAPE, SHR6, PW, and FLH every day (i.e., not only associated with hail events) when investigating the hail seasonal cycle from the parameters as the reanalysis data are more uniform in space. Reanalysis-2 is also used to obtain two different composites of large-scale flows: 1) the large-scale flows close to the times of hail occurrences and 2) the monthly mean flows. The two different composites are used to reveal the general characteristics of an environment in which certain hail events occur and the seasonal changes in the background flow conditions for the development of the hail events, respectively. For large-sized samples, a Student’s t test (Wilks 2011) is applied in order to evaluate whether or not the composite circulation of hail
events differs significantly from the climatological mean field at the 90% significance level. When the sample size is small, the bootstrap method is used to test the statistical significance, within which 1000 bootstrap samples are constructed for each meteorological field at each grid point. The 5% and 95% bootstrap estimates are then found to define the 90% confidence interval. The composite mean value should be significantly different from the climatological mean at the 90% confidence level when (i) the composite mean value appears between this confidence interval and (ii) the climatological mean value occurs outside this confidence interval.

3. Results

For the 1003 hail events distributed over the study area, we sort 673 (67.1%), 296 (29.5%), and 34 (3.4%) hail events with the MHDs of D1, D2, and D3, respectively. Clearly, small-sized-hail events occur more frequently whereas severe hail events are rare in China, as compared to those in the United States (Allen and Tippett 2015; Johnson and Sugden 2014). Figures 2a–d show the seasonal distribution of hail events with the MHDs of D1–D3 (denoted by different colors) across the study area. It is evident that hail events of different MHDs all exhibit significant seasonal variations. Hail season starts in the spring in South China and progresses northward to the north of 40°N during the summer, which is consistent with the results found in earlier studies (e.g., Zhang et al. 2008; Li et al. 2018). While all the hail events exhibit an obvious seasonal cycle, small- and large-sized hail events tend to occur more frequently in summer and spring, respectively (cf. Figs. 2c and 2b). Hail events with MHDs larger than 30 mm
occur mostly during the spring to the south of 35\degree N, and then shift to the north of 35\degree N in the summer.

a. Statistical characteristics of environmental parameters

Figure 3 shows the box-and-whisker plots of CAPE, SHR6, PW, FLH, and HGZ. For hail events in D1, D2, and D3, respectively, the median CAPE values are 857.9, 1146.9, and 2192.1 J kg\(^{-1}\) (Fig. 3a); the median SHR6 values are 15.47, 16.18, and 21.55 m s\(^{-1}\) (Fig. 3b); and the median PW values are 22.4, 27.6, and 34.8 mm (Fig. 3c). The CAPE of D3 ranges greatly from less than 1000 to about 3000 J kg\(^{-1}\) (taking the 25th–75th percentiles as criteria), indicating that even CAPE as small as 1000 J kg\(^{-1}\) can sustain large-sized hail as long as SHR6 and PW are large enough. The small sample size of D3 may also make the distinction difficult. SHR6 and PW for D3 cover relatively small ranges compared to those of D1 and D2. The 25th percentiles of SHR6 and PW for D3 are both larger than their median values of D1 and D2, implying that compared to CAPE, large SHR6 and PW are required for the occurrences of D3 hail events. This result is consistent with that of Brooks (2013), who showed that the intensities of tornadoes and hailstorms in the United States tend to be almost entirely a function of VWS, and depend only weakly on environmental thermodynamics (e.g., CAPE). The role of VWS is especially crucial for hailstorms with large MHDs (Allen et al. 2015). In general, larger MHD events are characterized with larger CAPE, stronger SHR6, and larger PW, albeit with little difference in SHR6 between D1 and D2.

The CAPE and SHR6 values for the D3 category, which are larger than those for the D1 and D2 categories (Fig. 3a), are comparable to those of the 38–44-mm hail-diameter category in Johnson and Sugden (2014).
Both the CAPE and SHR6 values for D3 are much larger than those in the Netherlands (Groenemeijer and Delden 2007) and Finland (Tuovinen et al. 2015), even though the study from Finland focuses on significant hail events with MHDs larger than 50 mm. Mean surface-based CAPE for severe hail occurring in southwestern Germany is 1250 J kg$^{-1}$, which is smaller than that in both China and the United States. Pöck et al. (2015) found a similar median MUCAPE of about 1000 J kg$^{-1}$ for severe hail events over central Europe. A recent study shows comparable CAPE and SHR6 values between 10–45-mm hail events in Turkey and 10–30-mm hail events in China (Kahraman et al. 2017). But either the CAPE or SHR6 of large-sized hail (i.e., >45 mm) event is still much smaller than that of large hail-sized events in China. The smaller CAPE in the above European countries than that in both China and the United States could be attributed to smaller lapse rates in the midtroposphere and lower moisture content in Europe (Brooks et al. 2003; Brooks 2009). Although the CAPE and SHR6 values for large hail-sized storms between China and the United States are comparable, many fewer severe hailstorms occur in China than in the United States, despite their similar latitudinal distributions. This result is similar to the finding of Brooks (2009) that the overall frequency of favorable CAPE–shear environments is less in Europe than in the United States.

The median FLH values for the D1, D2, and D3 hail events are 3830, 3991, and 4017 m, respectively (Fig. 3d). The median FLH for D1 is significantly different from that of D2 and D3 although there are large overlapping FLH values between the 25th and 75th percentiles. The generally lower median FLH values for D1 indicate that small-sized hail events in China need lower FLH, thus reducing melting. Although the HGZ thickness differs only at the 90% significant level between D1 and D3 (or D2 and D3), it tends to be thinner for larger MHD events, which is consistent with results found by Johnson and Sugden (2014). This could be easily understood because a thinner HGZ implies the presence of a larger negative lapse rate, which would facilitate the development of stronger updrafts. In addition, a thinner HGZ indicates that ice particles (e.g., hail embryos and supercooled water) would experience more collision and coalescence during hail growth.

Figures 4a–c show, respectively, the paired SHR6–CAPE, CAPE–PW, and SHR6–PW scatterplots associated with different MHD hail events. Note that only the paired SHR6–CAPE is plotted logarithmically, following Brooks (2009) and Allen et al. (2011). The SHR6–CAPE of D3 hail events shows a log–linear relationship: as long as SHR6 is large, even small CAPE can sustain D3 hail events, and when SHR6 is small, large CAPE is usually required (Fig. 4a). The phase space above the red fitting line [i.e., the linearly least square regression for the paired log(SHR6)–log(CAPE) parameters] indicates more favorable SHR6–CAPE conditions for D3 hail events. PW for most D3 hail events has values of 30 mm or larger (Fig. 4b), which is consistent with the results shown in Fig. 3. However, the paired CAPE–PW and SHR6–PW scatterplots do not exhibit any evidence of a linear relationship, as is the case for paired SHR6–CAPE.

b. Seasonal variations of environmental parameters

Table 1 shows the annual cycle of hail events with three different MHDs. Clearly, hail events in the smallest size bin D1 occur most frequently during the summer, with a peak in June (i.e., 20.5%), followed by August (15.4%) and July (14.8%).
as large CAPE, large PW, and small SHR6. In general, the average hail-favorable environmental parameters differ markedly from month to month. For example, the mean CAPE in March is 643 J kg$^{-1}$, and it increases to 1624 J kg$^{-1}$ in August. The mean SHR6 ranges from more than 25.5 m s$^{-1}$ in March to 12.6 m s$^{-1}$ in August. The mean PW in May is the smallest among the months of March–August.

The monthly distribution of hail occurrences for the D2 category differs from that of D1. Although June is still the peak month (22.3%), the hail-occurrence percentage (or frequency) becomes similar between March and April (12.8% and 14.9%), and between July and August (14.2% and 14.9%). The mean CAPE (SHR6) increases (decreases) from 1038 J kg$^{-1}$ (25.0 m s$^{-1}$) in March to 1977 J kg$^{-1}$ (12.3 m s$^{-1}$) in August (see Table 1). The mean PW is larger than 30 mm except for during the months of May (22.3 mm) and June (26.5 mm).

In contrast, about 58.8% of the D3 hail events take place during March and April, followed by June as a secondary peak accounting for 20.6% of the total D3 events. A further analysis of the results reveals quite different parameter values for large-hail events between spring and summer. That is, hail events take place under larger SHR6 but moderate CAPE in spring, while hail events in June have larger CAPE and moderate SHR6 (Table 1). The mean CAPE differs from 1051 J kg$^{-1}$ in March to 3004 J kg$^{-1}$ in July, while the mean SHR6 values for March and July are 24.5 and 14.1 m s$^{-1}$, respectively.

The above analysis indicates that the monthly distribution of D2 hail occurrences shares certain characteristics with those of the D1 and D3 hail events, respectively. This is understandable because of D2’s intermediate MHD range between D1 and D3. To better differentiate their characteristics, it is more logical to compare the environmental parameters between the two extreme categories (i.e., D1 and D3).

Before turning our attention to the two extreme MHD categories, it is necessary to mention that many environmental parameters for the month of May do not follow closely the general pattern of seasonal changes, especially for the frequencies of D2 and D3 events, except for CAPE (see Table 1). For example, PW values for all hail events during May are the smallest among the months of March–August (Table 1). A close examination of the geographical distribution of monthly hail events indicates that the May events take place mainly in central China, that is, west of 105°E and around 35°N, where not enough moisture is available through the EASM despite the presence of a reasonable CAPE (not shown). This factor can be seen from the large-scale background to be shown in the next subsection. Because of the relatively dry environments, only more significant D1 and smaller-sized hail events occur in May. The previously mentioned frequent occurrences of large-(small-) sized hail events in spring (summer), as shown in Figs. 2b and 2c, may result from the combined effects of multiple environmental parameters, as discussed in the next, and land surface conditions (e.g., topography).

To investigate why large-sized hail events occur more in spring than in summer and why the opposite is true for small-sized hail events within the context of the combined multiple environmental parameters, Fig. 5 shows the joint probability density function (PDF) for the paired SHR6–CAPE, CAPE–PW, and SHR6–PW parameters in March–August but excluding May for the reason mentioned above. Unlike the scatterplots given in Fig. 4, which show the required environmental conditions for hail occurrences, the PDF plots for the paired parameters given in Fig. 5 would help indicate to what extent the environmental parameters could be consistent with the hail-favorable conditions, thus providing a better understanding of their seasonal cycle. These PDFs are calculated from every single day (not just hail-occurrence days) of the above months during the years of 2008–15 in order to reveal the seasonal cycle of hail events from a viewpoint of the climatological probability of environmental parameters. Given the northward

---

**Table 1.** The mean values of PW (mm), SHR6 (m s$^{-1}$), CAPE (J kg$^{-1}$), and the percentage of hail events associated with different hail-size categories, occurring from March to August during 2008–15, within the MHD ranges (mm) of D1 (5, 10) mm, D2 [10, 30) mm, and D3 (≥30 mm). The mean values are listed in the last row.

<table>
<thead>
<tr>
<th></th>
<th>PW</th>
<th>SHR6</th>
<th>CAPE</th>
<th>%</th>
<th>PW</th>
<th>SHR6</th>
<th>CAPE</th>
<th>%</th>
<th>PW</th>
<th>SHR6</th>
<th>CAPE</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>25.6</td>
<td>25.5</td>
<td>643</td>
<td>9.2</td>
<td>31.0</td>
<td>25.0</td>
<td>1038</td>
<td>12.8</td>
<td>36.6</td>
<td>24.5</td>
<td>1051</td>
<td>29.4</td>
</tr>
<tr>
<td>Apr</td>
<td>22.8</td>
<td>19.0</td>
<td>877</td>
<td>10.4</td>
<td>33.7</td>
<td>20.4</td>
<td>1157</td>
<td>14.9</td>
<td>31.7</td>
<td>21.3</td>
<td>1647</td>
<td>29.4</td>
</tr>
<tr>
<td>May</td>
<td>17.8</td>
<td>17.7</td>
<td>890</td>
<td>11.9</td>
<td>24.2</td>
<td>17.6</td>
<td>1269</td>
<td>10.8</td>
<td>24.0</td>
<td>18.8</td>
<td>2785</td>
<td>8.8</td>
</tr>
<tr>
<td>Jun</td>
<td>25.8</td>
<td>15.2</td>
<td>1349</td>
<td>20.5</td>
<td>26.5</td>
<td>15.6</td>
<td>1210</td>
<td>22.3</td>
<td>32.1</td>
<td>18.0</td>
<td>2641</td>
<td>20.5</td>
</tr>
<tr>
<td>Jul</td>
<td>26.1</td>
<td>13.4</td>
<td>1390</td>
<td>14.9</td>
<td>31.0</td>
<td>13.3</td>
<td>1681</td>
<td>14.2</td>
<td>34.9</td>
<td>14.1</td>
<td>3004</td>
<td>11.7</td>
</tr>
<tr>
<td>Aug</td>
<td>25.0</td>
<td>12.6</td>
<td>1624</td>
<td>15.4</td>
<td>31.8</td>
<td>12.3</td>
<td>1977</td>
<td>14.9</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mean</td>
<td>20.3</td>
<td>18.3</td>
<td>754</td>
<td>—</td>
<td>27.3</td>
<td>18.6</td>
<td>1206</td>
<td>—</td>
<td>33.5</td>
<td>19.3</td>
<td>2014</td>
<td>2014</td>
</tr>
</tbody>
</table>

The above analysis indicates that the geographical distribution of monthly hail events for March–August 2018–15 in order to reveal the seasonal cycle of hail events from a viewpoint of the climatological probability of environmental parameters.

**DECEMBER 2018**

**LI ET AL.**

2823
seasonal shift of hail events, we select the red and blue box areas, shown in Fig. 2, as the foci for the months of March–April, June, and July–August. The red- and blue-boxed areas shown in Fig. 2 are used to calculate the joint probability density plots for March–April, June, and July–August. The fitting line in Fig. 4a is added to (a)–(c), and the 30-mm PW and the 15 m s\(^{-1}\) SHR6 lines in Figs. 4b and 4c are plotted in boldface in the (d)–(f) and (g)–(i), respectively.

It is evident from Figs. 5a–c that the general PDF pattern extends to larger CAPE and smaller SHR6 from spring to summer. Given larger SHR6 and smaller CAPE values in spring than those in summer, the largest probability density appears to be around 20 m s\(^{-1}\) in SHR6 and less than 200 J kg\(^{-1}\) in CAPE during spring. In summer, the largest PDFs of SHR6 and CAPE are centered at 10 m s\(^{-1}\) and less than 200 J kg\(^{-1}\), respectively (Figs. 5b and 5c). There are larger probabilities above the fitting line in spring than in summer, implying that hail-favorable SHR6–CAPE conditions for D3 events have a greater probability to occur during spring than in the summer. By comparison, the paired CAPE–PW plots, given in Figs. 5d–f, show more uniformly distributed PDFs for PW between 5 and 40 mm with CAPE less than 1000 J kg\(^{-1}\) in spring, which shifts to larger PW and CAPE during July and August. However, the peak PDF values are still far away from those averaged for D3 hail events during summer (Table 1). More significant differences between spring and summer are apparent in the paired SHR6–PW plots (Figs. 5g–i). There are two PDF centers in PW along the SHR6 of 20 m s\(^{-1}\) in the spring: one near 10 mm and the other around 30 mm (Fig. 5g). However, the opposite is true for summer (i.e., with large PW and smaller SHR6). If the PDFs of the paired SHR6–PW parameters are
compared to the corresponding scatterplots for D3 hail events (cf. Figs. 5g–i and 4c), more D3 hail events, occurring with SHR6 \( \geq 20 \, \text{m} \, \text{s}^{-1} \) and PW \( \geq 20 \, \text{mm} \), have larger probabilities in spring than in summer. This result indicates that hailstorms producing larger-sized hail are more likely to occur in a moister and higher sheared environment. However, high SHR6 and PW cannot always be present simultaneously over a large area of China. South China in spring is typically dominated by southwesterly monsoonal flows of warm and moist air in the lower troposphere and a pronounced upper-level jet providing high SHR6, while in summer south and central China is dominated by the EASM with abundant moisture supply but the absence of a significant upper-level jet. Only during March and April across South China may the environment conditions provide high SHR6–PW results (Fig. 5g), favoring the development of large-sized hail events, whereas the two parameters are negatively correlated during the summer. This seasonal cycle will be discussed in section 3c.

Now, we turn our attention to D1 hail events with their peak frequency in June. As mentioned before, the environmental CAPE in summer is much larger than that in spring, which provides higher probabilities for hailstorms to take place. Meanwhile, SHR6 does not seem to be significant for the D1 events. In addition, the paired CAPE–PW PDF shows similar structures in June and July–August. Then, one may ask: Why are small-sized hail events peaked in June rather than July and August? This question can be addressed by examining different behaviors occurring in the PDF of FLH during the two periods, as given in Fig. 6. That is, the largest PDF of FLH in June appears at around 4 km, which is typical for most hail events in China (Fig. 3), but it appears around 5 km for July–August. Since higher FLH allows more melting to occur, this would increase the possibility for small-sized hailstones to be melted before reaching the ground (Xie et al. 2010; Mahoney et al. 2012). This explains why D1 hail events should occur less frequently in July–August than in June.

In summary, the seasonal cycle of hail occurrences behaves to a large extent as the variation of environmental parameters following the seasonal changes. Large environmental PW–SHR6 values in spring favor large-sized hail events even if CAPE is relatively small (e.g., mean CAPE values of 1051 J kg\(^{-1}\) in March and 1647 J kg\(^{-1}\) in April compared to 2767 J kg\(^{-1}\) during the summer). Small-sized hail events take place more frequently in the summer, during which period the PW and CAPE are large and SHR6 is small. June is the peak month for small-sized hail events because the lower mean FLH in June decreases the melting effects. As a result, large-sized hail occurrences tend to peak in March and April in South China, whereas small-sized hail occurrences peak in June over most of East China.

c. Composite hail-favorable environmental flows for two extreme MHD events

The environmental parameters discussed in the preceding subsection are closely related to large-scale flows. Thus, it is desirable to examine the composite large-scale flow structures associated with the hail events with two extreme MHDs in order to help understand how hail-favorable environments differ from hail-unfavorable ones. As mentioned previously, large-sized hail events in March and April are selected to reflect the synoptic conditions during the spring. During our early examination, we noted different synoptic flow structures associated with large-sized hail events to the west (S1) and east (S2) of 110°E, due likely to the different influences of the Qinghai–Tibet Plateau. Thus, the composite analyses for the two different scenarios will be investigated separately.

Figure 7 shows the large-scale circulation composite for D3 hail events occurring to the west of 110°E (i.e., S1) during the spring. The 200-hPa circulation is featured with one jet stream of 45 m s\(^{-1}\) near 25°N (Fig. 8a), which is consistent with the large SHR6 found above. In addition, a negative temperature anomaly (Fig. 7b) is seen over South China, which coincides with negative geopotential height (GPH) anomalies at 500 hPa. All of these findings imply the presence of reduced static stability and favorable quasigeostrophic forcing in the midtroposphere for more intense convective development, given enough PW and low-level lifting. At the low levels, the area of focus is covered by a positive temperature anomaly at 850 hPa (Fig. 7c) and dominated by...
southwesterly flows associated with a subtropical high that brings warm and moist air into the D3 occurrences region (i.e., 20°–26°N, 100°–120°E; Fig. 8d). However, PW over the region during spring does not differ significantly from the monthly mean PW, indicating that moisture supply is not a limiting factor for large-sized hail events over S1. On the other hand, the positive (negative) 850- (500-) hPa temperature anomalies and the 200-hPa wind speed all pass the significance test, demonstrating the importance of large CAPE and VWS for large-sized hail events over S1.

Of interest is that large-sized hail events occur to the east of 110°E with positive temperature anomalies (i.e., up to 2°C) (Fig. 8b), in contrast to those occurring to the west of 110°E where negative temperature and GPH anomalies prevail. This implies that the negative temperature and GPH anomalies are not the necessary conditions for the generation of large-sized hail events over S2. The hail-favorable conditions over S2 include the presence of an upper-level jet stream (Fig. 8a) giving rise to large SHR6, strong lower-level southwesterly flows (dark-orange vectors in Fig. 8d) that help transport more moisture (i.e., higher PW; green shadings covered by black dots), and larger positive temperature anomalies at 850 and 700 hPa than those at 500 hPa, indicating significant lower-level warmth. Furthermore, the convergence between southwesterly and northerly flows helps trigger deep convection and facilitate the development of well-organized thunderstorms. However, most of these features differ significantly from the climatological mean, suggesting that the hail-favorable conditions for large-sized events over S2 are more
closely related to the lower-level warmth and moisture supply.

The large-scale circulation composite for D1 hail events during summer over North China is given in Fig. 9, showing much weaker VWS values than those of D3 hail events in spring (cf. Figs. 9a and 7a). The D1 hail-favorable areas are also covered with negative GPH and a temperature anomaly at 500 hPa (Fig. 9b), smaller than the ±1°C temperature anomalies at both 700 and 850 hPa, as well as a low-level cyclonic circulation over northeast China with a southerly flow of relatively warm and moist air (Figs. 9c,d). Although PW < 20 mm occurs over a large area, as is also shown in Fig. 3c, it still favors the generation of D1 hail events. These results are consistent with those of Li et al. (2016), who found that warm-season hail events over North China occur often during the passage of cold-frontal systems with the colder midtroposphere and relatively lower FLH. These circulation characteristics also suggest the importance of reduced static stability and increased moisture supply in determining the D1 hail-favorable environments during summer over North China. The above analyses confirm the characteristics and seasonal variation of environmental parameters associated with D1 and D3 hail events, as revealed in section 3b, and they also demonstrate that these environmental parameters are consistent with the hail-favorable synoptic circulations.

The above seasonal variation in hail-favorable environments can be better seen from the monthly mean circulation patterns, as given in Fig. 10. South China and East China during March are influenced by an upper-level jet stream providing strong SHR6; the distribution of −10°C isotherm at 500 hPa (Fig. 10a), above which level hail begins to grow; and southwesterly monsoonal flows transporting warm and moist air into the region (Fig. 10b). Subsequently, the upper-level jet stream decreases in intensity, while the northeastward transport of the lower-level warm and moist air increases, as reflected by large PW values (Figs. 10c and 10d). The above circulation patterns are consistent with the high SHR6 and PW conditions over South China, as shown in Fig. 5. Together with the presence of cold air aloft, the monthly mean circulation patterns during March and April favor the environmental parameters required by large-sized hail events. With the surface temperature rising, May is a transition month from spring to summer with the onset of the EASM (Tao and Chen 1987; Ding 1992; Ding and Chan 2005), and the northward displacement of the upper-level jet (Fig. 10c). More importantly, a 700-hPa trough over the Qinghai-Tibet...
Plateau deepens (Fig. 10f), which helps expand the areas of high PW northward up to 35°N. High PW and high SHR6 are out of phase (cf. Figs. 10e and 10f), thus limiting the development of D3 hail events.

The monthly mean synoptic flows in summer, given in Fig. 11, show large PW and warm 700-hPa temperatures over South China and East China, contributing to large CAPE shown in Fig. 5. The upper-level jet is much weaker in June and nearly absent in July and August, which is consistent with the smaller SHR6 results discussed before. The midtroposphere in June is colder than in July and August, as can be seen from the −10°C isotherm at 500 hPa that is displaced from 40°N to about 44°N over time. This corresponds well to the relatively lower FLH over North China in June than in July and August (cf. Figs. 11a,c,e and 6). In the lower troposphere, south to southwest monsoonal flows transport warm and moist air to South China, accounting for the presence of high PW over the hail-favorable region (Figs. 11d–f). However, the warmer midlevel air may favor hail melting processes. Thus, in the absence of strong VWS and an intrusion of colder air in the midtroposphere, small-sized hailstones or graupel may not reach the ground despite the presence of an abundant moisture supply.

In summary, large-sized hail events mainly occur during the spring prior to EASM onset with intense SHR6 and sufficient moisture supply while small-sized hail events mainly occur during summer with high CAPE and PW but weak SHR6. The latter is consistent with the northeasterward progression of the warm and moist EASM air into North China and frequent intrusions of midtropospheric cold and dry air, both contributing to the presence of large CAPE. Because of the presence of a weak upper-level jet stream and the lack of a strong midtropospheric cold-air intrusion providing appropriate FLH, small-sized hail events occur frequently in North China during the summer, especially in June. By comparison, large-sized hail events occur more frequently during the spring over South China in the presence of both the upper-level jet stream and the warm moist southwesterly flows in the lower troposphere, but with their intensities stronger and weaker than those during summer in North China, respectively. Few hail events occur during the summer over South China because of the presence of the warmer midtroposphere and weak VWS.

4. Discussion

South China and East China are regions under the influence of the EASM with a distinct annual cycle (Webster et al. 1998). This is especially true for many
rainfall events occurring in China (Ding 1992; Qian 2000; Ding and Chan 2005; Wang et al. 2004). Of course, hail events are more complicated than ordinary rainfall events because of the important role of ice microphysical processes. Hail growth requires the presence of an abundant moisture supply, strong updrafts, and cold air in the middle to upper troposphere. Thus, the interaction of the EASM flows of different intensities with midlatitude disturbances gives rise to different environmental characteristics for the development of hailstorms in South and North China. For example, during the EASM season, intense cold fronts with marked vertical tilting occur typically over North China, whereas after moving to South China the cold fronts are much weaker and shallower when interacting with weak-gradient monsoonal flows (Ding 1992; Ninomiya 2004; Ding and Chan 2005). Downstream advection of the warm PBL air from the Qinghai–Tibet Plateau tends to contribute negatively to CAPE but more positively to melting, especially for small-sized hailstones, as they fall through the midlevel warm air. Consequently, the hail season in South China may start prior to the onset of the EASM while the hail season in North China would last even long after the summer monsoon onset.

To place these results into context, Brooks et al. (2007) examined the annual cycle of hail-favorable
environmental parameters in the United States, and found that SHR6 (CAPE) decreases (increases) over the central plains from spring to summer. They found the mean CAPE to be much larger than that in North China during the summer and in South China during the spring, which are the two main hail seasons in China. The large CAPE in the central plains of the United States appears to be attributable to the presence of large temperature lapse rates under the influence of the Rocky Mountains and high moisture content as a result of the northward transport of warm and moist air from the Gulf of Mexico by an intense southerly low-level jet (LLJ) (Brooks et al. 2003). Perhaps one of the major differences in hail-favorable environments between the two countries is that North America experiences comparatively little influence from a summer monsoon (Webster 1987; Wang and Ding 2006). In contrast, South China is dominated by a deep warm and moist layer from the surface to 500 hPa and higher under the influence of the summer monsoonal flows and the Qinghai–Tibet Plateau. However, the environmental CAPE in China is typically greater than that in Europe (Brooks et al. 2007). This is likely due to Europe’s higher latitudes, where the water vapor content, under relatively colder air, is lower (Brooks et al. 2003) compared to that in both China and the United States. Meanwhile, given such relatively smaller CAPE environments (e.g., Van Delden and Groenemeijer 2007; Kunz and Puskeiler 2010; Tuovinen et al. 2015), the convective initiation process through synoptic forcing and interactions with the local topography may contribute more to the development of hailstorms in Europe (Brooks 2009).
As for the hail size issue raised in section 1, we note that hail events of larger than 19-mm MHD are frequently observed in the United States but are rare in China. The former could be attributed to the presence of large CAPE and high vertical shear, leading to the development of supercell thunderstorms. The large CAPE is more closely associated with the intense surface heating and the northward transport of warm and moist air to the east of the Rocky Mountains (Bonner 1968; Rife et al. 2010), while the high vertical shear could be related to the presence of an LLJ or the southward intrusion of an upper-level jet stream. In contrast, few low-level jets are observed over North China (Du et al. 2014). The MHD in most hail events in China falls in the United States’ smallest hail diameter range of 19–25 mm (or even smaller). The mean diameter in this range has been decreasing during the past 35 years, which is consistent with the findings that global warming has decreased the overall occurrences of small-sized hail events through enhanced melting (Mahoney et al. 2012; Tippett et al. 2015; Brimelow et al. 2017).

It should be mentioned that China has a wide range of complex topography and landscapes, which could account for large regional differences in the hailstorm climatology (Zhang et al. 2008; Li et al. 2016). Hail events over different regions tend to display various characteristics of environmental parameters, even though the desert areas over northwest China and the Tibetan Plateau are excluded in this study. This implies that hail-favorable environmental parameters should be investigated regionally, especially for D3 hail events. In addition, more environmental parameters, such as helicity, with different hail size bins over different regions could be examined in the future.

One may note that many of the outliers for CAPE, SHR6, and PW are largest for the small MHD category (Figs. 3a–c). This phenomenon may be related to the presence of high aerosol loading in China that can increase ice nuclei (IN) concentrations. High IN concentrations would produce more ice crystals and may result in stronger updrafts (Ekman et al. 2007), thereby increasing small-sized hailstones (Fan et al. 2010; Deng et al. 2018; Liu et al. 2018). On the other hand, Liu et al. (2018) noted little impact of increased IN concentrations on updraft intensity, since hail formation is favored when updrafts are strong enough to transport more supercooled water into the upper troposphere. Thus, the dynamic impact of IN on hail formation still remains as an important area for future studies.

5. Summary and conclusions

In this study, the spatiotemporal characteristics of hail events and hail-favorable proximity environments during the period of 2008–15 in China were investigated using hail observations, L-band rawinsondes, and global reanalysis data. A total of 1003 hail events with an MHD of greater than 5 mm were examined, with 3.4% of them producing extreme MHDs of larger than 30 mm. Hail events of different MHDs all show significant seasonal variations with June being the peak month for small MHDs and large MHDs in March–April. Large-MHD events are more frequently observed in South China than in North China. Results show that MHDs tend to increase with higher CAPE, larger SHR6, and higher PW. In general, environments for the extreme MHDs of greater than 30 mm have median PW values of 33.4 mm, CAPE values of 2192 J kg⁻¹, and SHR6 values of 21.5 m s⁻¹; the latter two are comparable to those observed in the United States. Large CAPE values, which contribute to hailstorm intensity differences between the two geographical locations, are less frequently observed in China than across the central plains of the United States. Small-sized hail events tend to experience lower FLHs, while large-sized hail events occur with thinner HGZ thicknesses.

Hailstorms in China tend to develop in a synoptic circulation pattern with an upper-level jet stream providing a deep-layer VWS, a lower-level southwestward flow transporting warm and moist air, and a mid-tropospheric cold-air intrusion giving large lapse rates as well as enough PBL development to precondition a hail-favorable environment. Hailstorms occurring in South China usually have larger VWS but smaller CAPE than those in North China. The seasonal variation of the hail-favorable environment is largely regulated by the EASM. Hail season starts during the spring in South China prior to the onset of the EASM (i.e., in middle May) as southwesterly flows associated with the subtropical high bring warm and moist air into the lower troposphere while relatively cold air still prevails aloft. After the onset of the EASM, South China is dominated by warm and moist monsoonal flows that extend from the middle to the upper troposphere, and the hail-favorable conditions shift to North China, where cold-frontal systems are juxtaposed with low-level southwesterly flows as the subtropical high moves northeastward.

In conclusion, we may state that the hail-favorable environments and MHD characteristics in China differ in some aspects from those observed in the United States and the other geographical locations, despite the presence of many similarities. These differences appear to be attributable mainly to the influences of the Qinghai–Tibet Plateau and the EASM. Since this is the first study to examine and document the spatiotemporal characteristics of hail-favorable parameters and proximity of environmental conditions associated with different MHDs,
more studies are needed to gain further insight into the different hail-favorable conditions meridionally and zonally across China. In particular, hail events with high-resolution in situ and remote sensing observations, including various types of radar observations, should be investigated to validate the generality of the results presented herein. Cloud-resolving modeling studies with sophisticated ice microphysical processes are also needed to determine the sensitivity of hail growth to various hail-favorable parameters and environmental conditions found in this study, and compare them to those observed in the other geographical locations.

Acknowledgments. This work was supported by the National Basic Research Program of China (973 Program: 2014CB441402), the National Natural Science Foundation of China (Grant 41330421) and Basic Research and Operation Funding of the Chinese Academy of Meteorological Sciences (Grant 2018Y009). DLZ was also supported by the U.S. Office of Naval Research Grants N000141410143 and N000141712210. The authors are grateful to the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA) for providing hail size observation data.

REFERENCES


