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# A Hail Climatology in Mongolia

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**Abstract:** The temporal and spatial characteristics of hail frequency in Mongolia are examined using the hail observation data from 61 meteorological observatories for 1984-2013. The annual number of hail days averaged over all observatories and the entire period is 0.74. It exhibits a decreasing trend, particularly since 1993 with a rate of decrease of 0.214 per decade. Hail occurrence is concentrated in summer, with 72% of the total hail days occurring in June, July, and August. Moreover, hail occurrence is concentrated in the afternoon and early evening, with 89% of the total hail events occurring between 1200 and 2100 local standard time (LST). Spatially, observatories where relatively frequent hail events are observed are concentrated in the north central region where almost all of the land is mountainous or covered by grassland, whereas relatively less frequent hail events are observed in the southern desert region. The relationship between hail frequency and thermodynamic factors including the convective available potential energy (CAPE), the temperature lapse rate between 700 and 500 hPa, the water vapor mixing ratio averaged over the lowest 100 hPa layer, and the freezing-level height is examined using the ERA-Interim reanalysis data. It is found that in summer, CAPE and the low-level water vapor mixing ratio are larger on hail days than on all days, but there is no clear relationship between hail frequency and the 700-500 hPa temperature lapse rate. It is also found that annually, CAPE and the low-level water vapor mixing ratio decrease, while the freezing-level height increases, which seems to be responsible for the annually decreasing trend of hail frequency in Mongolia.

**Key words:** Hail frequency in Mongolia, Convective Available Potential Energy (CAPE), temperature lapse rate, water vapor mixing ratio, freezing-level height

## 1. Introduction

Hailstorms have received much attention because of their disastrous impacts and distinct cloud microphysical aspects such as extreme riming process. A Hailstorm is meso-$\gamma$ scale convective phenomenon, which can cause considerable damage to crops, livestock, houses, and even humans (Cao, 2008). Hailstones are produced through extreme riming in convective clouds. The diameter of a hailstone is typically ~1 cm, but hailstones of 10-15 cm have also been observed (Houze, 2014). The microphysics of hailstones and the dynamics of storms that can produce hailstones have been extensively studied in recent decades [see Pruppacher and Klett (1997) and Houze (2014)]. Moreover, the long-term climatology of hail in many regions of the world has been documented (Table 1).

Previous studies of long-term hail climatology are summarized in Table 1. Here, only studies that used hail observation data spanning at least 10 years are considered. The third column of Table 1 indicates the trend of annual hail frequency. For example, Ontario in Canada and southwestern Germany exhibit increasing trends of annual hail frequency over the last two decades (Cao, 2008; Kunz et al., 2009). The Korean Peninsula exhibits a long-term decreasing trend of hail frequency (Kim and Ni, 2015; Jin et al., 2017). Moreover, there are regions that show no clear trend with regard to the annual hail frequency (e.g., Giaiotti et al., 2003; Simeonov et al., 2009; Berthet et al., 2011). These results imply that the temporal and spatial characteristics of hail differ, depending upon the geographical location and regional atmospheric flow/circulation features. Some attempts have been made to connect the trend of annual hail frequency to thermodynamic factors. Kunz et al. (2009) established a relationship between the annual hail frequency and convective indices depending on temperature and moisture in the lowest layer. Li et al. (2016) attributed the decrease of annual hail frequency in northern China to the increase of convective inhibition (CIN) as well as weakened synoptic troughs in East Asia. Jin et al. (2017) related the decrease of annual hail frequency in South Korea to the increase of freezing-level height and the decrease of vertical wind shear.

Hartmann et al. (2013) noted that it is difficult to describe climate change-related trends of small-scale severe weather phenomena, such as hailstorms, because of the inhomogeneity of the observational data. For example, the trend of annual hail frequency in Tuovinen et al. (2009) is described as “unclear” in Table 1 in spite of an apparent increase since the late 1990s because the increasing trend is partially attributed to the more efficient collection of reports by the Finnish Meteorological Institute.

Mongolia experiences frequent hailstorms, sometimes with hailstorm-related damage. Geographically, Mongolia is located at a high altitude (85% of the country exceeds 1000 m in elevation), with rolling plateaus that occupy a large portion of the country. There are mountain ranges in the western and northern parts of Mongolia, the Gobi Desert in the southern part, and grasslands in the eastern part (Fig. 1). Moreover,

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**Table 1.** Previous studies of long-term (here spanning at least 10 years) hail climatology. Study area, references, and annual trend are listed. The stars (*) in references indicate that the study area is the part of the country. Annual trend is written as "unclear" when the annual trend is too weak to determine or when it is mentioned in the study that the annual trend is affected by the inhomogeneity of data. Annual trend is written as "region-dependent" when the annual trend is an increase or a decrease depending on regions of the country.

| Study area | References | Annual trend |
|---|---|---|
| Asia | | |
| China | Zhang et al. (2008) | |
| | Li et al. (2016) | decrease |
| North Korea | Kim and Ni (2015) | decrease |
| South Korea | Jin et al. (2017) | decrease |
| Turkey | Kahraman et al. (2016) | increase since 2005 |
| Europe | | |
| Alpine region | Nisi et al. (2016) | decrease since 2009 |
| Bulgaria | Simeonov et al. (2009) | unclear |
| Central Europe | Suwala and Bednorz (2013) | |
| Finland | Tuovinen et al. (2009) | increase since the late 1990s |
| France | Dessens (1986)* | unclear |
| | Vinet (2001) | |
| | Berthet et al. (2011) | unclear |
| Germany | Kunz et al. (2009)* | increase |
| Greece | Kotinis-Zambakas (1989) | |
| | Sioutas et al. (2009)* | unclear |
| Italy | Giaiotti et al. (2003)* | unclear |
| | Baldi et al. (2014) | |
| Romania | Burcea et al. (2016) | region-dependent |
| United Kingdom | Webb et al. (2001) | unclear |
| North America | | |
| Canada | Etkin and Brun (1999) | unclear |
| | Cao (2008)* | increase |
| United States | Changnon (1977) | region-dependent |
| | Changnon and Changnon (2000) | decrease since 1970s |
| | Schaefer et al. (2004) | unclear |
| South America | | |
| Argentina | Mezher et al. (2012) | region-dependent |
| Oceania | | |
| Australia | Schuster et al. (2005)* | unclear |

Mongolia has been considerably affected by climate change, experiencing an annual mean near-surface temperature increase of 2.14°C during the past 70 years (Dagvadorj et al., 2009). These geographical and climatic features can provide the distinctive temporal and spatial characteristics of hail frequency in Mongolia, which is the motivation behind the present study.

In this study, a long-term hail climatology in Mongolia is documented, presenting the temporal and spatial distributions of hail frequency. In addition, hail frequency is related to thermodynamic factors such as CAPE, temperature lapse rate between 700 and 500 hPa, mixing ratio averaged over the lowest 100 hPa layer, and freezing-level height. In section 2, the data used in this study are described. In section 3, the analysis results are presented and discussed. In section 4, a summary is given.

## 2. Data

The first systematic meteorological observation network of Mongolia was established in 1936. However, the observation periods of some observatories were not continuous for hail records before 1984. For the homogeneity of data, we use the hail observation dataset for the period of 1984-2013 provided by the National Agency for Meteorology and Environment Monitoring of Mongolia. Figure 1 shows the locations of 61 meteorological observatories which have been fully operational during the 30-year period of 1984-2013. The dataset includes information on the time and duration of hail occurrence, which was recorded manually. Hail is recorded only if hailstones fall inside the observation area. Observers in Mongolia distinguish hail based on the definition of hail, a type of precipitation in the form of balls or lumps of ice (Changnon, 1977), although a specific diameter criterion is not provided.

To represent hail frequency in this study, a hail day is defined as a day during which hail was observed one or more times at an observatory, and the term "hail frequency" in this study means the frequency of hail days. Moreover, to describe hail frequency at an observatory, the annual mean hail frequency and the monthly mean hail frequency are defined following Zhang et al. (2008) and Jin et al. (2017). The annual mean hail frequency is the average number of hail days at an observatory per year (i.e., the number of hail days at the observatory divided by the number of years), while the monthly mean hail frequency is the average number of hail days at an observatory during each month per year (i.e., the number of hail days in a particular month at the observatory divided by the number of years).

To examine the relationship between hail frequency and thermodynamic factors in Mongolia, atmospheric sounding data are required. However, only one station (Ulaanbaatar) has launched radiosondes regularly in Mongolia during the last 30 years. Therefore, instead of using radiosonde data, the ERA-Interim reanalysis data provided by the European Centre for Medium-Range Weather Forecasts are used. The reanalysis data are interpolated to the locations of the 61 meteorological observatories. Then, the aforementioned thermodynamic factors (i.e., CAPE, 700-500 hPa temperature lapse rate, average water vapor mixing ratio in the lowest 100 hPa layer, and freezing-level height) are calculated.

The ERA-Interim reanalysis data contain atmospheric ther-

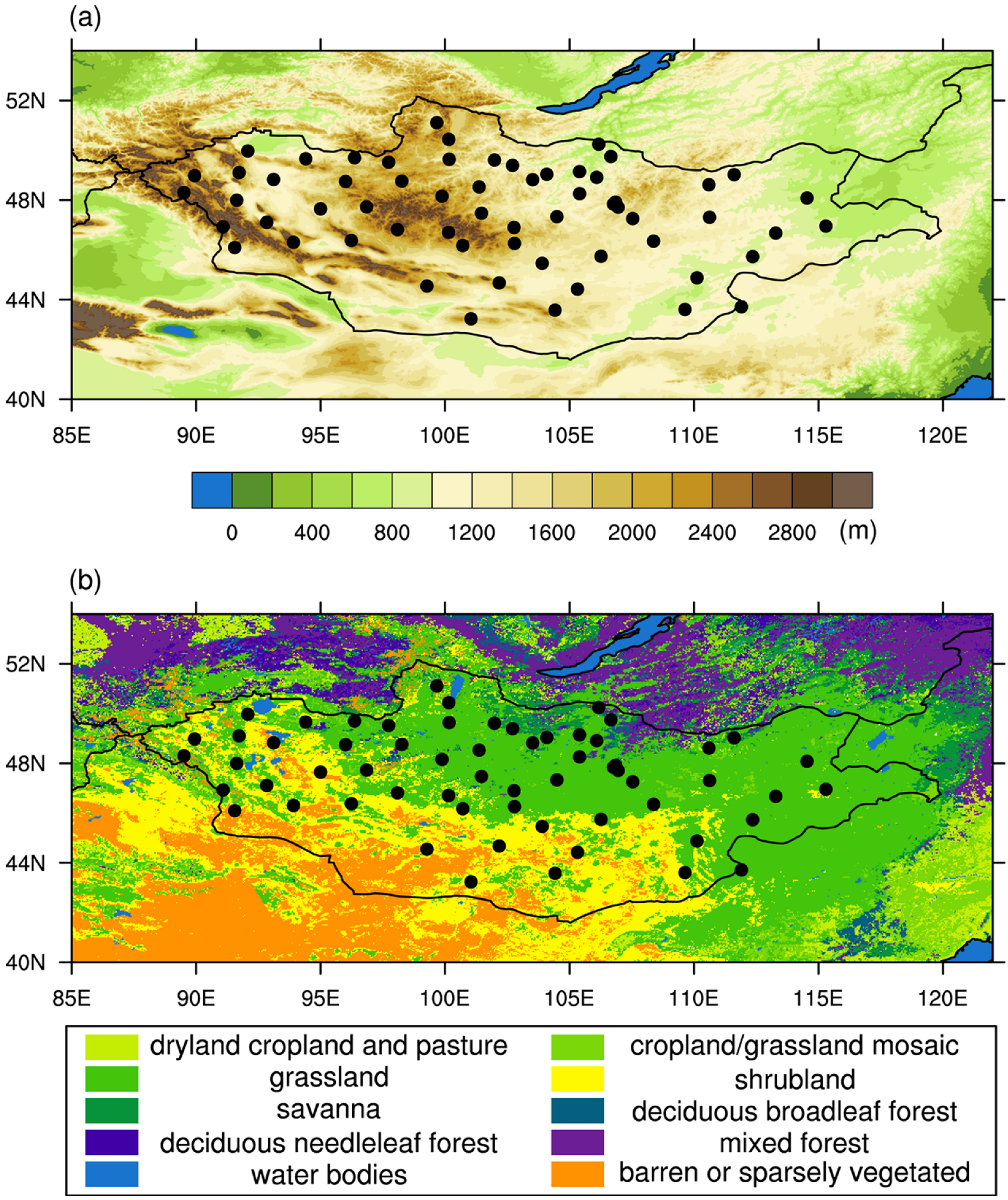

**Fig. 1.** (a) Terrain height and (b) land use in Mongolia. Locations of 61 meteorological observatories are indicated in closed circles. Information on the terrain height and land use is from the United States Geological Survey (USGS).

modynamic data in time intervals of four times a day [0200, 0800, 1400, and 2000 local standard time (LST)]. The hail occurrence in Mongolia is extremely concentrated in the afternoon (see Fig. 4). Therefore, only the data at 1400 LST are chosen to calculate the thermodynamic factors on hail days. Moreover, for reasonable comparison of the thermodynamic factors between all days and hail days, only the data at 1400 LST are also chosen to calculate the thermodynamic factors on all days.

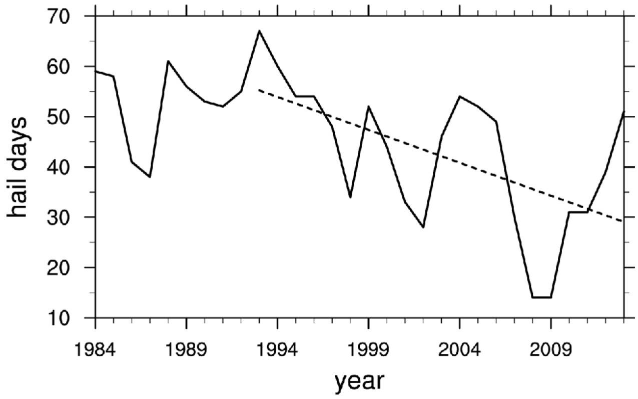

**Fig. 2.** Annual variation of the number of hail days. The dashed line indicates the linear trend since 1993.

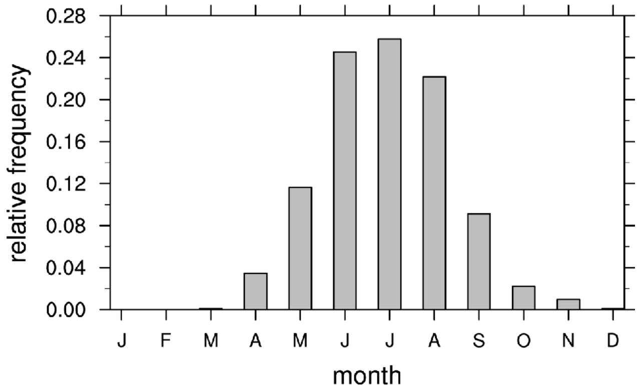

**Fig. 3.** Monthly variation of the relative frequency of hail days.

## 3. Results and discussion

### *a. Temporal and spatial characteristics of hail frequency*

A total of 1358 hail days were reported from the 61 meteorological observatories in Mongolia for the period of 1984-2013. Hence, the annual mean hail frequency averaged over all observatories and the entire period is 0.74 (i.e., 0.74 hail days per year on average). The annual mean hail frequency in Mongolia is relatively low compared to that in Inner Mongolia in China averaged over the period 1961-2005 (Zhang et al., 2008), which is located southeast of Mongolia.

Figure 2 shows the annual variation of the number of hail days. Although the number of hail days exhibits large fluctuations, it clearly shows an annually decreasing trend, particularly since 1993. The decreasing trend of hail days is also evident in China (Xie et al., 2008; Li et al., 2016), United States (Changnon and Changnon, 2000), North Korea (Kim and Ni, 2015), and South Korea (Jin et al., 2017). Using the linear regression method, it is found that the decreasing rate of the annual number of hail days since 1993 is 0.214 per decade and statistically significant at the significance level of 95% (see the dashed line in Fig. 2).

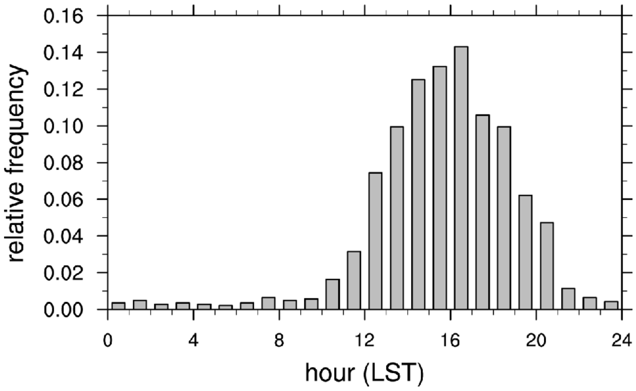

**Fig. 4.** Diurnal variation of the relative frequency of hail occurrence.

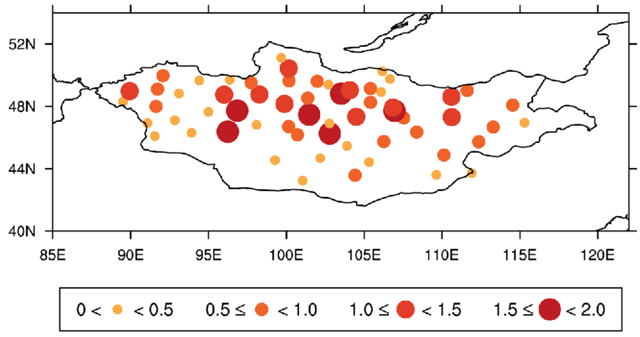

**Fig. 5.** Spatial distribution of annual mean hail frequency.

Figure 3 shows the monthly variation of monthly mean hail frequency averaged over all observatories. The monthly variation is represented in terms of the relative frequency of hail days, which is the total hail days in a certain month divided by the total hail days in the entire period. Seventy-two percent of the total hail days are concentrated in summer (June, July, and August). The high hail frequency in summer is commonly observed in inland regions (central United States: Changnon, 1977; north central China: Zhang et al., 2008; parts of inland Europe: Punge and Kunz, 2016). Hail is rarely observed in winter (December, January, and February) and March due to the strong influence of the Siberian high. Some studies have reported that hail is most frequent in April or October/November in some regions mainly due to the large instability in the middle level of the troposphere (southern China: Zhang et al., 2008; South Korea: Jin et al., 2017), while only 7% of the total hail days occur in April, October, and November in Mongolia.

The diurnal variation of the relative frequency of hail occurrence is shown in Fig. 4. It is noted that multiple hail occurrence in one hail day is taken into account to examine the diurnal variation of hail occurrence. Hail occurrence is mostly concentrated in the afternoon and early evening. The maximum relative frequency of hail occurrence is 0.147 at 1600-1700 LST. Eighty-nine percent of the total hail events occur

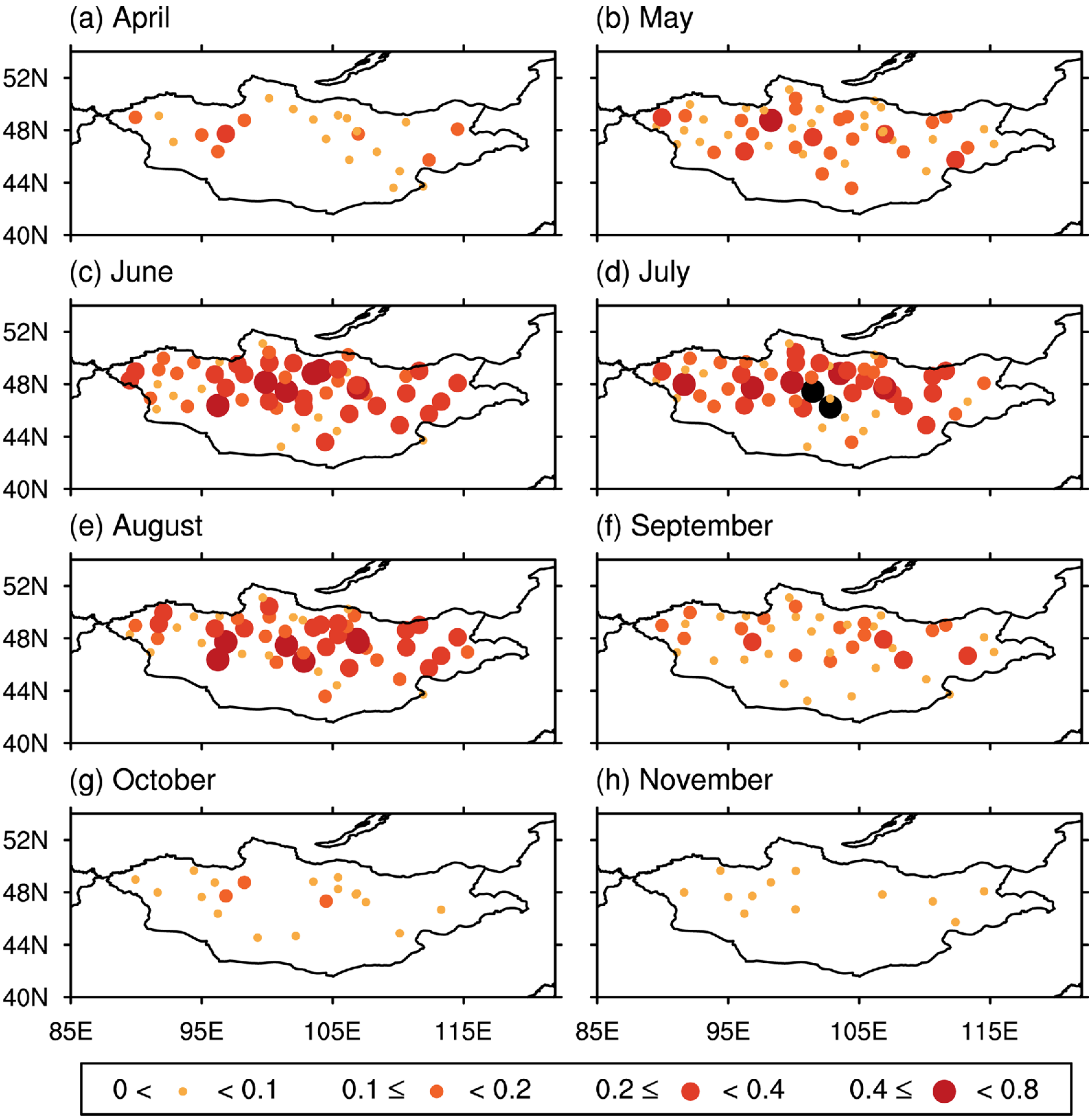

**Fig. 6.** Spatial distributions of monthly mean hail frequency in (a) April, (b) May, (c) June, (d) July, (e) August, (f) September, (g) October, and (h) November. The black circles in (d) are Arvaikheer (46.26°N, 102.79°E) and Tsetserleg (47.47°N, 101.46°E) which exhibit the highest monthly mean hail frequency in July, 0.77.

between 1200 and 2100 LST. Strong daytime solar radiation raises the near-surface temperature, resulting in the increase of the temperature lapse rate. The induced atmospheric instability provides a favorable condition for convection, which may be a main reason for the high hail frequency in the afternoon (Punge and Kunz, 2016).

Figure 5 illustrates the spatial distribution of annual mean hail frequency in Mongolia. In the northern region of the country, where most of the land is grassland and the overall terrain height is relatively high (Fig. 1), the annual mean hail frequency exhibits a high spatial variability. At some observatories in the northern region of the country, the annual mean hail frequency is higher than 1, while at the other observatories of this region, the annual mean hail frequency is less than 0.5. In the northern region of the country, even if the distance between two observatories is close, the annual mean hail frequency tends to show a large difference. However, it should be noted that a large number of observatories with relatively high hail frequency are located in the north central region of the country, where almost all of the land is mountainous or covered by grassland. Mountainous terrain can divert flows and cause low-level flow convergence, parts of which may contribute to a high hail frequency (Nisi et al., 2016). The high hail frequency in the north central region may have been affected by the orography and relatively wet atmospheric condition compared to the western and southern regions covered by shrubland or desert (see Fig. 1b). In contrast to the north central region, hail seldom occurs in the southern region of the country, where most of the region is desert (the Gobi Desert). The annual mean hail frequency in the southern region is generally less than 0.5. The extremely dry conditions are largely responsible for the low annual mean hail frequency in the southern region, because hail is less likely to occur in dry conditions (see Fig. 7c).

Figure 6 illustrates the spatial distributions of monthly mean hail frequency in each month, from April to November. Hail events are observed in April, except in the southern desert region. In May, the hail frequency increases at almost all observatories, with a few observatories showing the maximum monthly mean hail frequency [e.g., Tosontsengel (48.76°N, 98.26°E), with a maximum monthly mean hail frequency of 0.43]. Throughout the country, the monthly mean hail frequency is generally the highest in June, July, and August. The maximum monthly mean hail frequency reaches 0.77 at Arvaikheer and Tsetserleg (black circles in Fig. 6d) in July. The monthly mean hail frequency decreases drastically beginning in September at almost all observatories. In October and November, the monthly mean hail frequency is less than 0.2 at all observatories.

### *b. Relationship between hail frequency and thermodynamic factors*

Many thermodynamic and dynamic factors that affect hail occurrence are known. These factors include CAPE, temperature lapse rate, low-level moisture supply, freezing-level height, vertical wind shear, jet stream, and cold fronts (e.g., Dessens, 1986; Vinet, 2001; Zhang et al., 2008; Tippett et al., 2015; Jin et al., 2017). To examine possible links between the characteristics of hail frequency in Mongolia and thermodynamic factors, CAPE, the temperature lapse rate between 700 and 500 hPa, the water vapor mixing ratio averaged over the lowest 100 hPa layer, and the freezing-level height are considered in this study.

Figure 7 shows the relative frequency distributions of thermodynamic factors calculated on hail days and all days of June, July, and August. It is observed that the relative frequency for large CAPE, large low-level water vapor mixing ratio, and low freezing-level height is higher on hail days than on all days. That is, CAPE is larger, the low-level water vapor mixing ratio is larger, and the freezing-level height is lower on hail days than on all days in summer. The mean CAPEs averaged over hail days and over all days are 161.2 and 79.1 J kg$^{-1}$, respectively. The mean low-level water vapor mixing ratios averaged over hail days and over all days are 7.05 and 6.34 g kg$^{-1}$, respectively. The freezing-level height averaged over hail days and over all days are 3680 and 3842 m, respectively. Therefore, it can be said that large CAPE, large low-level water vapor mixing ratio, and low freezing-level height are related to the high hail frequency in summer. The midlevel temperature lapse rate is also known to affect hail occurrence in some regions of the world (Farnell and Llasat, 2013; Allen et al., 2015; Jin et al., 2017). Figure 7b shows that the relative frequency for large midlevel temperature lapse rate is slightly higher on hail days than on all days. However, the difference is small, with no statistical significance. It seems that the midlevel temperature lapse rate has little relationship with the hail occurrence in Mongolia. The midlevel temperature lapse rates averaged over hail days and over all days are 6.71 and 6.65 K km$^{-1}$, respectively.

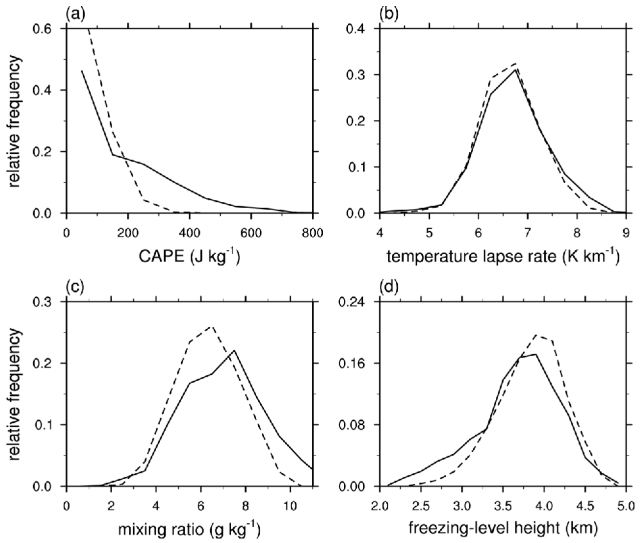

**Fig. 7.** Relative frequency distributions of (a) CAPE, (b) the temperature lapse rate between 700 and 500 hPa, (c) the water vapor mixing ratio averaged over the lowest 100 hPa layer, and (d) the freezing-level height in summer. Solid and dashed lines indicate the hail days and all days, respectively.

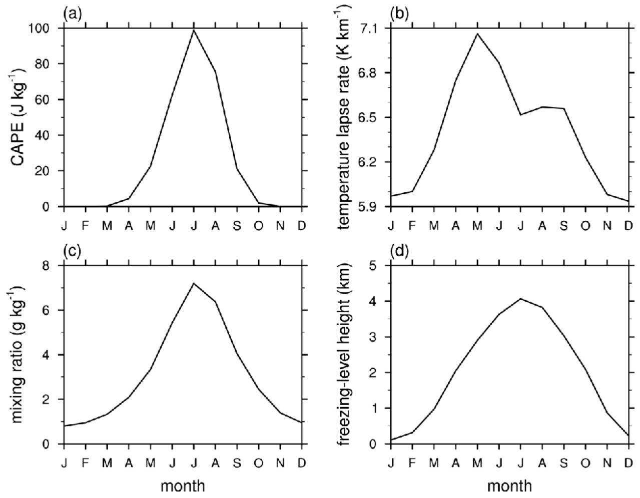

**Fig. 8.** Monthly variations of (a) CAPE, (b) the midlevel temperature lapse rate, (c) the low-level water vapor mixing ratio, and (d) the freezing-level height on all days.

The monthly variations of the thermodynamic factors on all days are shown in Fig. 8. As expected, CAPE and the low-level water vapor mixing ratio exhibit their peaks in July, which might affect the maximum hail frequency in July. The

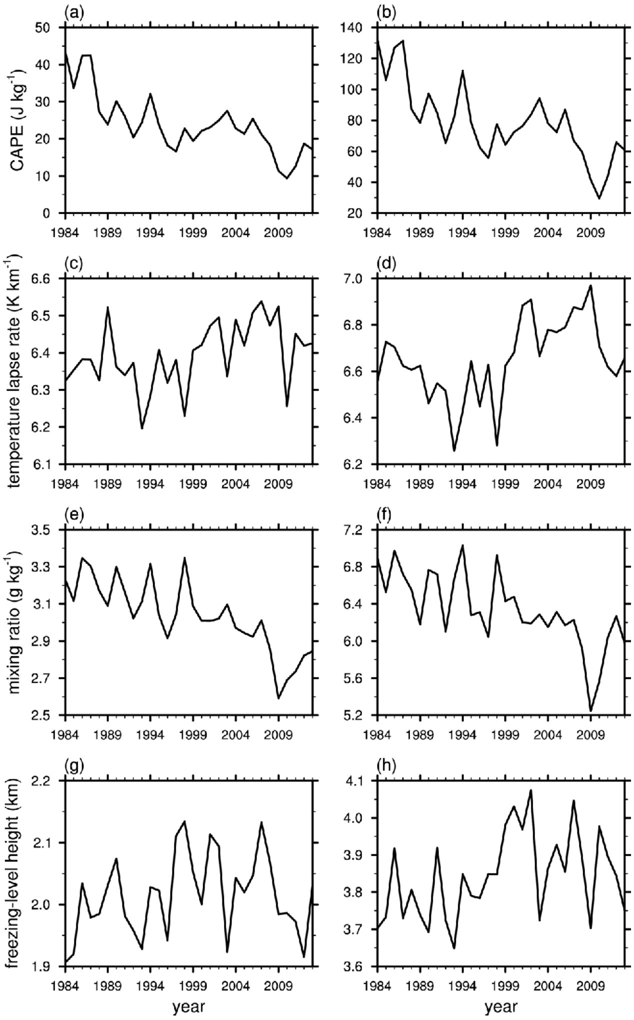

**Fig. 9.** Annual variations of whole-year averaged (a) CAPE, (c) midlevel temperature lapse rate, (e) low-level water vapor mixing ratio, and (g) freezing-level height. (b), (d), (f), and (h) are the same as (a), (c), (e), and (g), respectively, but averaged over summer.

freezing-level height is the highest in July due to warm air. CAPE and the low-level water vapor mixing ratio play important roles in the high hail frequency in summer. CAPE and low-level water vapor amount are also important factors to summer precipitation. It is noted that precipitation shows a maximum in summer in Mongolia (Doljinsuren and Gomes, 2015), and heavy rainfall in Mongolia is occasionally accompanied by hail occurrence (Goulden et al., 2016). To investigate common and different atmospheric conditions for hail occurrence and heavy rainfall, further research examining thermodynamic/dynamic factors is needed. The midlevel temperature lapse rate peaks in May, possibly due to the frequent passage of cold fronts (Jambaajamts, 1989). However, the hail frequency in May is not very high. The midlevel temperature lapse rate shows a local minimum in July, during which the hail frequency is the highest. It seems that the monthly variation of hail frequency is largely affected by CAPE and the low-level water vapor mixing ratio, whereas the midlevel temperature lapse rate does not show any significant relationship with the hail frequency. It is hypothesized that hail occurrence is generally attributed to both low-level water vapor amount and atmospheric instability such as midlevel temperature lapse rate. Because of the relatively dry atmospheric condition of the country, the relative importance of the midlevel temperature lapse rate is small compared to that of the low-level water vapor mixing ratio. This could be a possible reason for the different monthly variation of hail occurrence in Mongolia from that in wetter regions (e.g., southern China: Zhang et al., 2008; North Korea: Kim and Ni, 2015; South Korea: Jin et al., 2017). Further research is needed to quantify the importance of the midlevel temperature lapse rate.

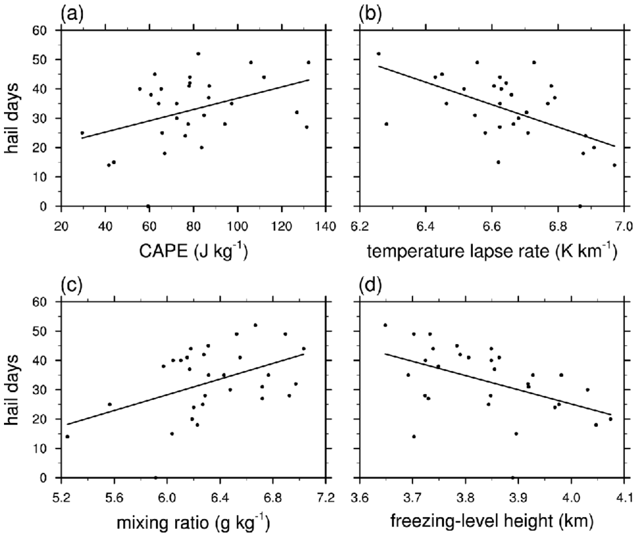

**Fig. 10.** Scatter plots of the number of hail days and (a) CAPE, (b) the midlevel temperature lapse rate, (c) the low-level water vapor mixing ratio, and (d) the freezing-level height for each year. The thermodynamic factors are averaged over summer of each year.

Besides thermodynamic factors, there could be dynamic factors or atmospheric circulations that are related to hail occurrence in Mongolia. Li et al. (2016) discussed that the weakened 850-hPa meridional wind is responsible for the decreasing trend of annual hail frequency in northern China, which is close to Mongolia. Vertical wind shear is known to be related to the development of supercell storms that can produce severe weather (Groenemeijer and van Delden, 2007; Jin et al., 2017). Two additional factors, which are the low-level meridional wind and the vertical wind shear, are examined for hail days and all days. It is revealed that the average low-level horizontal wind in summer in Mongolia is weak. The weak circulation in summer is less likely to affect the change of annual hail frequency significantly. It is also revealed that there is no noticeable relationship between the vertical wind shear and hail occurrence in Mongolia.

To examine the relationship between the decreasing trend of the number of annual hail days in Mongolia (Fig. 2) and thermodynamic factors, the annual variations of the thermodynamic factors averaged over the entire year and over summer are shown in Fig. 9. CAPE exhibits a decreasing trend. Since CAPE is very small in the other seasons (Fig. 8a), the decreasing trend in CAPE is mainly due to the decrease in CAPE in summer (Fig. 9b). The low-level water vapor mixing ratio also exhibits a decreasing trend, which becomes clear in the 2000s. The freezing-level height in summer exhibits an increasing trend, although its annual variation is somewhat large. Therefore, the changing trends of CAPE, the low-level water vapor mixing ratio, and the freezing-level height seem to be closely related to the decreasing trend of the number of annual hail days, whereas the midlevel temperature lapse rate increases slightly annually, which might act to increase hail occurrence.

Scatter plots of the number of hail days and the thermodynamic factors averaged over summer are shown in Fig. 10. All the correlations between the thermodynamic factors and the number of hail days are statistically significant at the significance level of 95%. CAPE and the low-level water vapor mixing ratio show positive correlations with the number of hail days, i.e., the number of hail days tends to be larger in the years with larger CAPE and larger low-level water vapor mixing ratio. The correlation coefficients of CAPE and the low-level water vapor mixing ratio with the number of hail days are 0.40 and 0.45, respectively. The freezing-level height shows a negative correlation with the number of hail days, which indicates that the increase in freezing-level height is related to the decrease in the number of hail days. The correlation coefficient between the freezing-level height and the number of hail days is −0.47. The midlevel temperature lapse rate is negatively correlated with the number of hail days, i.e., the number of hail days tends to be smaller in the years with larger midlevel temperature lapse rate. This is in opposition to the previous result which indicates that the large midlevel temperature lapse rate might result in high hail frequency (e.g., Jin et al., 2017). More detailed analysis is needed to clarify the relationship between midlevel temperature lapse rate and hail frequency.

## 4. Summary

In this study, we examined the long-term hail climatology in Mongolia and its association with the thermodynamic environment using the hail observation data from 61 meteorological observatories for 1984-2013. The average number of annual hail days is 0.74, and exhibits a decreasing trend since 1993. Seventy-two percent of the total hail days are concentrated in summer, and 89% of the total hail events are observed between 1200 and 2100 LST. Observatories where relatively frequent hail events are observed are concentrated in the north central region. In contrast, hail events are observed less frequently in the southern desert region. In summer, CAPE and the low-level water vapor mixing ratio are larger on hail days than on all days, while the relationship between the hail frequency and the 700-500 hPa temperature lapse rate is not clear. CAPE and the low-level water vapor mixing ratio show an annually decreasing trend, while the freezing-level height shows an annually increasing trend. These trends are responsible for the annually decreasing trend of the number of hail days in Mongolia.

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