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A hail climatology in South Korea

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ABSTRACT

A hail observation dataset for 1972–2013 is analyzed to examine the temporal and spatial distributions of hail occurrence in South Korea. Furthermore, using radiosonde data, three thermodynamic factors which are 700–500 hPa temperature lapse rate, water vapor mixing ratio in the lowest 100 hPa, and convective available potential energy (CAPE) and one dynamic factor which is 0–6 km bulk wind shear are calculated and their correlations with hail occurrence in South Korea are examined. Hail days per year in South Korea show a decreasing trend. The monthly variation of hail days exhibits double peaks in April and November. The minimum value of hail days appears in August, which is related to the high freezing-level height, the small midlevel temperature lapse rate, and the weak bulk wind shear. During a day, 44% of the whole hail events occur between 1200 and 1800 local standard time. Spatially, hail primarily occurs in the west coastal area and the east mountainous area of South Korea. Both the regions exhibit double peaks in the monthly variation of hail days, but the east mountainous area exhibits the later spring peak (May) and the lower hail frequency in late autumn compared to the west coastal area. The midlevel temperature lapse rate is strongly correlated with the monthly variation of hail occurrence. Hail is likely to occur when the low-level water vapor mixing ratio is in the range of ~3–6 g kg^{-1}. CAPE is not strongly correlated with hail occurrence. The strong bulk wind shear is correlated with hail occurrence. The bulk wind shear is decreasing and the freezing-level height is increasing annually, which contributes to the annual decrease of hail occurrence.

1. Introduction

Hailstorms are severe weather events and can cause considerable damages to crops and agricultural facilities on a local scale and within a short duration. To cope with hailstorm-related disasters appropriately, the climatology of hail needs to be studied.

Many studies of hail climatology have been performed in the past decades. Changnon (1977) analyzed the pattern of temporal and spatial distributions of hail occurrence on various scales in the United States, finding that the most hail-favorable region is along and in the lee of the Rocky Mountains. The topographical features of the Rocky Mountains also appear to be important to hail climatology in Canada (Etkin and Brun, 1999). Punge and Kunz (2016) reviewed European hail climatology studies. Hail is likely to occur in warm season (April to September) in most of European countries except for some coastal regions where the climate is significantly influenced by the Mediterranean Sea and the Atlantic Ocean. In some regions of Europe (e.g., southern France), dense hailpad networks are established so that the researches using high-resolution data with the information of hailstone size distribution are available (e.g., Sanchez et al., 2009). Zhang et al. (2008) examined hail climatology in China for 45-year period. Hail peak months vary from early spring in the southern region to summer in the Tibetan Plateau. The northeastern region exhibits two peaks in May/June and September. China has experienced a significant decrease of hail frequency except for the southern region (Li et al., 2016). Kim and Ni (2015) showed that North Korea also exhibits a significant decrease of hail frequency.

Some studies made an effort to find a favorable condition for hail. Brooks et al. (2003) used thermodynamic and dynamic factors such as temperature lapse rate, convective available potential energy (CAPE), lifting condensation level, and bulk wind shear to identify favorable environments for severe thunderstorms with hail. Merino et al. (2013) found the synoptic environment favorable for hailstorms in Mid-Ebro Valley where the hail frequency is very high is characterized by a trough at 500 hPa with a cold air mass over the west side of the Iberian Peninsula, inducing a low-level warm advection and midlevel positive vorticity advection. They also showed that CAPE larger than 500 J kg^{-1} can be an important forecast parameter for hailstorms in that region.

Hail has been observed and recorded at meteorological observatories in South Korea. Using the Korea Meteorological Administration (KMA) records, previous studies investigated the hail climatology in South Korea. Lim et al. (2000) examined characteristics of temporal and spatial distributions of hail occurrence and the relationship between hail occurrence time and mesoscale circulation for 10 years from 1989 to 1998. Kim et al. (2001) examined statistical features of

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hail occurrence for 10 years from 1991 to 2000 in the east mountainous area of South Korea where hail damages are big. Because these studies did not cover a long-time period, the hail climatology in South Korea needs to be updated to include a longer period and recent data.

Although South Korea is not a geographically large country, topography is complex and synoptic and mesoscale atmospheric features are distinct with season. These can result not only in a peculiar seasonal distribution but also in a distinct spatial distribution of hail occurrence. In this study, we document a hail climatology in South Korea for the 42-year period 1972–2013, presenting annual, monthly, and diurnal variations and geographical distribution of hail occurrence. Year 1972 is the year when many new meteorological observatories opened. Additionally, in this study, an effort is made to find the factors that affect hail occurrence in South Korea. Lim et al. (2000) used the wet-bulb zero height influenced by the amount of low-level moisture as a factor affecting hail occurrence. In this study, three thermodynamic factors which are 700–500 hPa temperature lapse rate, water vapor mixing ratio in the lowest 100 hPa, and CAPE and one dynamic factor which is 0–6 km bulk wind shear are used to find their relations to hail occurrence.

The datasets used in this study are described in Section 2. The analysis results are presented and discussed in Section 3. In Section 4, a summary is given.

2. Data

Two datasets are used in this study. First, a hail observation dataset for the period 1972–2013 provided by KMA is used. This dataset includes the information for the time of hail occurrence and hailstone size, which were recorded manually. The red circles in Fig. 1 show locations of 32 meteorological observatories. It is noted that hail is recorded only if hailstones fall inside the observation area.

Hail is defined as a class of precipitation in the form of lumps of ice (Changnon, 1977). Since the shape and formation process of hail are similar to those of ice pellets or graupel, KMA has a diameter criterion of distinguishing hail from ice pellets or graupel, which is 5 mm. However, in some cases, some observers recorded ice pellets with diameters smaller than 5 mm as being hail, considering the damage to nearby areas or the type of precipitating clouds. This consideration was not applied to every observatory, so data of hail with diameters smaller than 5 mm are excluded in the present analysis.

In this study, a hail day means a day during which hail was observed once or more at an observatory and is used as a measure of hail frequency. Following Zhang et al. (2008), the annual-mean hail frequency at an observatory is defined as the mean number of hail days per year (i.e., the number of hail days at the observatory divided by the number of years of observation), and the monthly-mean hail frequency at an observatory is defined as the mean number of hail days in each month per year (i.e., the number of hail days in a particular month at the observatory divided by the number of years of observation).

For the analysis related to the atmospheric conditions favorable for hail formation, the atmospheric sounding dataset is used in this study. From this dataset, 700–500 hPa temperature lapse rate, water vapor mixing ratio averaged over the lowest 100 hPa layer, CAPE, and 0–6 km bulk wind shear are calculated. The atmospheric sounding data observed using radiosonde launched from Osan and Gwangju stations (Fig. 1) are used to calculate thermodynamic factors for all days (hail days plus non-hail days). The radiosonde observation began in 1973 and 1979 at Osan and Gwangju stations, respectively, and has been made four times per day [0300, 0900, 1500, and 2100 local standard time (LST)].

Hail observation data from 7 stations where radiosonde observations are made (Fig. 1), including Osan and Gwangju stations, are considered for selecting hail days for which thermodynamic factors are

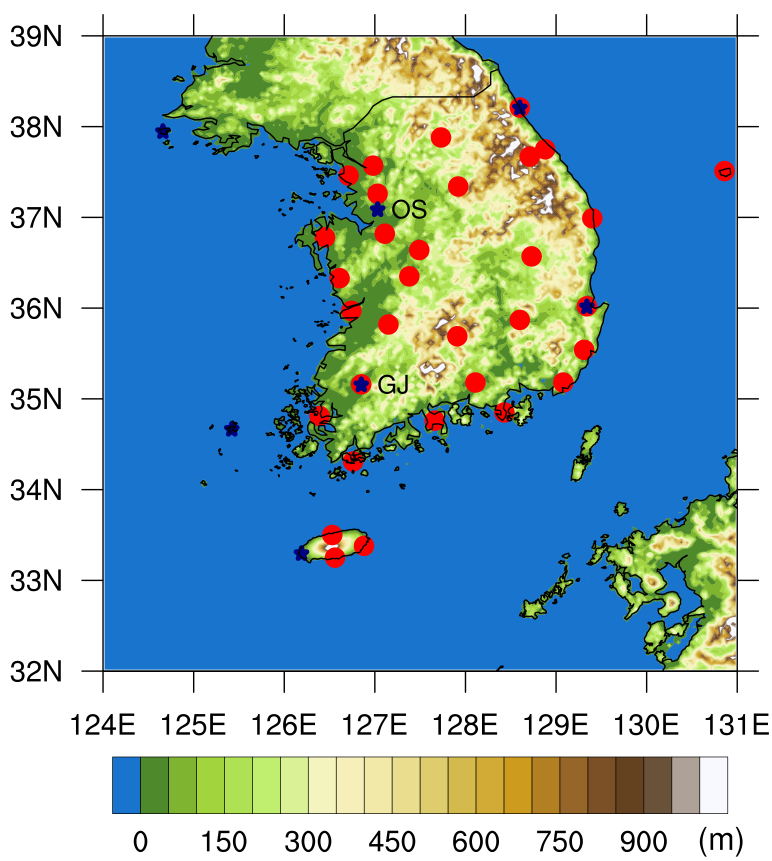

Fig. 1. Topographic height (color), locations of 32 meteorological observatories with hail records for the 42-year period from 1972 to 2013 (red circles), and locations of 7 radiosonde stations (navy stars) in South Korea. Osan and Gwangju are marked with the navy stars labelled OS and GJ, respectively.

calculated. The data from three of the stations are excluded to construct hail climatology because of their relatively short observation periods, starting from 1988, 2000, and 2003, respectively. It is noted that because hail observation is not made at Osan station, hail observation data at Suwon observatory (located just north of Osan station, see Fig. 1) are matched to the atmospheric sounding data at Osan station. At the 5 stations except Osan and Gwangju stations, the radiosonde observation is made twice per day (0900 and 2100 LST). The number of radiosonde soundings for hail days at the 7 stations is 54.

For a hail event, the atmospheric sounding data at the station are chosen to calculate thermodynamic factors. Because the radiosonde observation interval is somewhat long, there are some hail events that have no sounding data within a close time. So a criterion to choose the sounding data that adequately represent the thermodynamic condition related to hail occurrence is established. Considering that the atmospheric instability would be released after hail occurrence and that the observation long before the hail occurrence may not be representative, the observation interval is divided into two parts. If a hail event occurred at Osan (Suwon) or Gwangju station which has 6-h observation intervals and if the event occurred during the first 4 h of the observation interval, the observation immediately before the event is regarded as the most representative; if the event occurred during the last 2 h of the observation interval, the observation immediately after the event is chosen. For example, if a hail event occurred at 1200 LST at Gwangju station, observation at 0900 LST is used, and if a hail event occurred at 1400 LST, observation at 1500 LST is used. If a hail event occurred at one of the other 5 stations, the same guideline for choosing atmospheric sounding data as for Osan and Gwangju stations is applied, except that the observation interval is divided into the first 8 h and the last 4 h.

3. Results and discussion

3.1. Temporal distribution

For the period 1972–2013, 392 hail days were reported from the 32 meteorological observatories. The annual-mean hail frequency averaged over all the 32 observatories is 0.29. The annual variation of hail days is illustrated in Fig. 2. The number of hail days fluctuates strongly from year to year, but it is apparent that there is a decreasing trend of hail days. The decreasing rate of annual-mean hail frequency averaged over all observatories is 0.09 per decade. The annual decreasing trend of hail frequency was also reported in the United States (Changnon and Changnon, 2000), China (Xie et al., 2008; Li et al., 2016), the latitude band between 30°S and 45°S in Argentina (Mezher et al., 2012), part of southwestern France (Hermida et al., 2013), and North Korea (Kim and Ni, 2015). Xie et al. (2008) pointed out that the increase in freezing-level height due to global warming induces the decreasing trend of hail frequency in China. Li et al. (2016) attributed the decreasing trend of hail frequency in northern China to the weakening of the monsoon

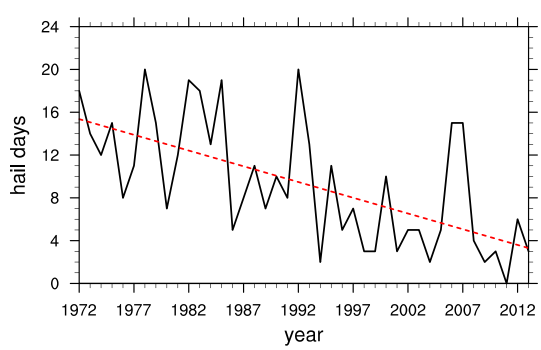

Fig. 2. Annual variation of hail days and its linear trend. The equation of the trend line is $y = -0.29(x - 2013) + 3.4$ ($R^2 = 0.39$).

circulation in East Asia. In this study, it will be shown that the freezing-level height and the 0–6 km bulk wind shear exhibit statistically significant relationships with the annually decreasing trend of hail frequency in South Korea. It is noted that the decreasing trend of hail frequency in this study is larger than that in Lim et al. (2000). One reason for the difference is that Lim et al. (2000) did not exclude hail occurrence with hailstones smaller than 5 mm in diameter. As the freezing-level height in South Korea has increased, hailstones with smaller diameters may have been more affected, causing the change of the annual trend of hail days. The annual variation of hail days in each season is shown in Fig. 3. The hail days decrease most noticeably in autumn (September–November). The decreasing trend of annual-mean hail frequency in each season is statistically significant only in autumn and winter. The decreasing rates of annual-mean hail frequency in autumn and winter are 0.05 and 0.02 per decade, respectively.

The monthly variation of hail days is shown in Fig. 4, which is expressed in terms of relative frequency. Previous studies indicate that the peak of hail occurrence usually appears in late spring or summer (e.g., Etkin and Brun, 1999; Giaiotti et al., 2003; Schuster et al., 2005; Simeonov et al., 2009; Sioutas et al., 2009; Mezher et al., 2012; Suwala and Bednorz, 2013; Kahraman et al., 2016). However, hail in South Korea occurs most frequently in November, followed by April, which produces a double peak structure of monthly variation. 29% of hail occurs in the first peak (April and May), and 47% occurs in the second peak (October to December). The peak in late autumn is a rare phenomenon across the globe. In the United States, which covers a variety of geography and climate, only the lee of the Great Lakes shows an autumn maximum of hail frequency (Changnon, 1977). In Cyprus, a maximum hail frequency is observed in December (Michaelides et al., 2008), and in western Greece, a high hail frequency is observed in cold period, October to March (Sioutas, 2011). In South Korea, cold air advection in the midlevel and upper level occurs frequently in spring and autumn. The large midlevel temperature lapse rate induced by the cold air advection can be a primary reason for the high hail frequency in the peak seasons, which will be discussed in Section 3.3.

The relatively small value of hail days in wintertime (January and February) is due to the high stability of the atmosphere and the lack of moisture in the lower layer (e.g., Longley and Thompson, 1965; Dessens, 1986; Vinet, 2001; Zhang et al., 2008; Farnell and Llasat, 2013). Small midlevel temperature lapse rate and small water vapor mixing ratio in the lower layer in wintertime provide unfavorable conditions for hail occurrence (see Figs. 9b and 10b).

The minimum value of hail hays appears in August, despite the relatively low stability and the abundant moisture in the lower layer. Similar features are observed in China (Zhang et al., 2008). That study found that hail is rare in the wet season in the eastern part of northeast China and also rare in southern China which is the wettest area. One reason for low hail frequency in summer is the high freezing-level height. In summer, with the warm atmosphere, the freezing-level height is located higher. This makes produced hailstones fall for a longer time, and they are finally observed as rainfall at the surface due to melting in the warm lower layer of the atmosphere (Foote, 1984; Lim et al., 2000). Another possible reason is related to the midlevel temperature lapse rate, which is relatively small in summer (see Fig. 9b). Farnell and Llasat (2013) found that the hail occurrence in Catalonia is related to the significant midlevel temperature lapse rate in middle levels. Sohn et al. (2013) analyzed characteristics of precipitation over the Korean Peninsula during July–September using satellite data and showed that heavy rainfall over the Korean Peninsula is more associated with clouds whose tops are not very high. In addition, the weak bulk wind shear in summer can also be related to the low hail frequency in summer (see Fig. 12b). It has been pointed out that the strong vertical wind shear is strongly related to the supercell storm development (e.g., Weisman and Klemp, 1982; Bunkers et al., 2006). In a case study, Korosec (2009) showed that the strong vertical wind shear is related to the rapid organization of an isolated storm into a severe hailstorm. In South Korea, the bulk

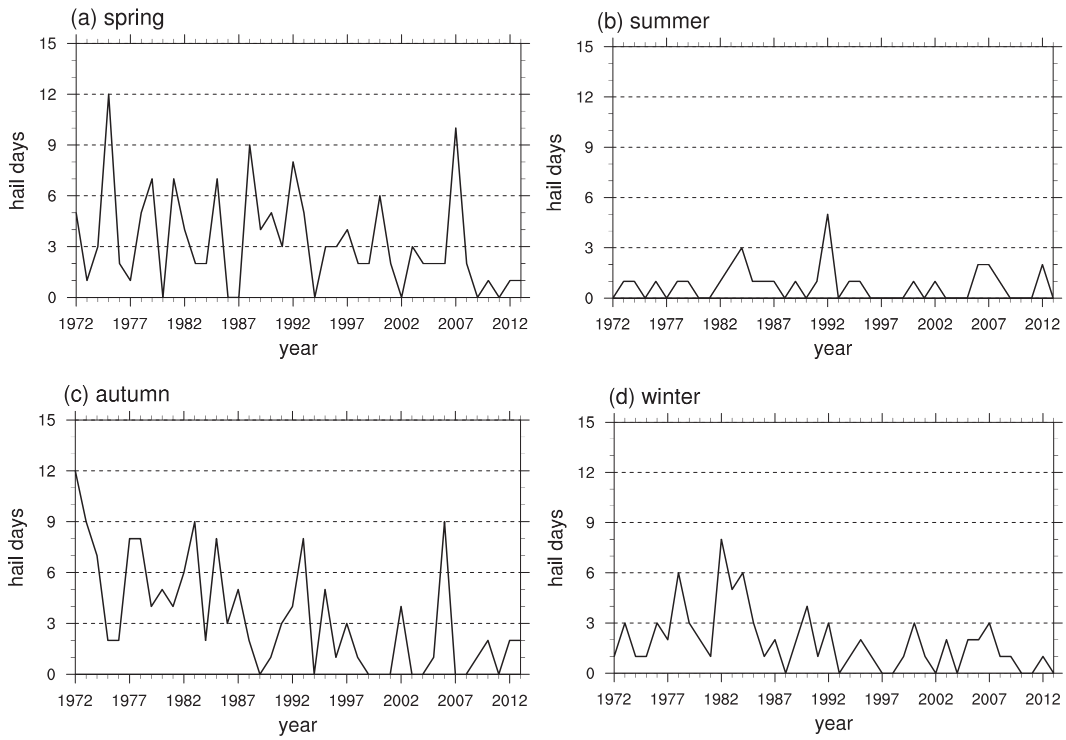

Fig. 3. Annual variations of hail days in (a) spring (March–April–May), (b) summer (June–July–August), (c) autumn (September–October–November), and (d) winter (December–January–February). Only the annual trends of hail days in autumn and winter are statistically significant at the significance level of 95%. The changing rates in (c) and (d) are −0.16 and −0.06, respectively, which means that the decreasing rates of the annual-mean hail frequency in autumn and winter are 0.05 and 0.02 per decade, respectively.

wind shear is the weakest in summer, which is not a favorable condition for hail formation.

During a day, the hail occurrence is concentrated in the afternoon (Fig. 5). 44% of the whole hail events occur between 1200 LST and 1800 LST. An afternoon peak of hail occurrence is observed in almost all areas around the world (e.g., Dessens, 1986; Giaiotti et al., 2003; Schuster et al., 2005; Zhang et al., 2008; Tuovinen et al., 2009). The strong surface heating during the daytime induces the instability of the atmosphere, thereby making the favorable conditions for hail occurrence.

3.2. Spatial distribution

The spatial distribution of the annual-mean hail frequency is shown in Fig. 6. The two boxes in Fig. 6 represent groups of locations that have relatively high annual-mean hail frequency. Hail in South Korea occurs relatively frequently in the west coastal area (the blue box in Fig. 6) and the east mountainous area (the black box in Fig. 6). There are 7 observatories in the west coastal area (C1 to C7) and 3 observatories in the east mountainous area (M1, M2, and M3). Because observatory M1 (the triangle in Fig. 6) started observation from 1987, it was not included in the 32 observatories that have observed hail from 1972. However, the data from observatory M1 are used in the comparison for better analysis (see Fig. 8b). C1 and C4, which belong to the west coastal area group, have 0.60 and 0.74 hail days per year, respectively. Both M2 and M3, which belong to the east mountainous area group, have 0.50 hail days per year. However, hail rarely occurs in the east coastal area and the southeastern area. The annual-mean hail frequencies in these areas are less than 0.2.

The monthly variations in the spatial distribution of hail frequency are examined. Fig. 7 shows the monthly-mean hail frequency of all the 32 observatories in each month. In January, February, and March, the monthly-mean hail frequency is near zero at almost all the observatories. In April, some west coastal observatories show an increase in hail frequency. In May, the hail frequency at the west coastal observatories

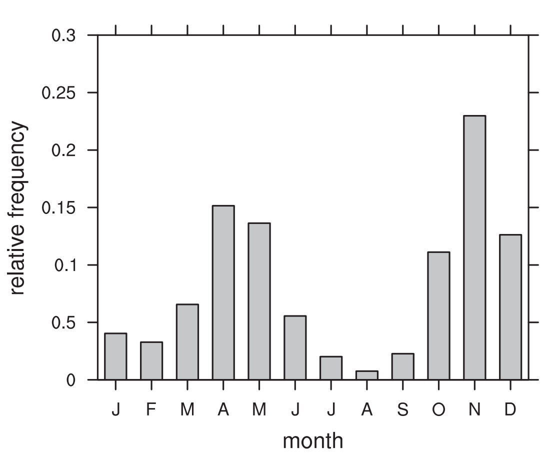

Fig. 4. Monthly variation of hail days.

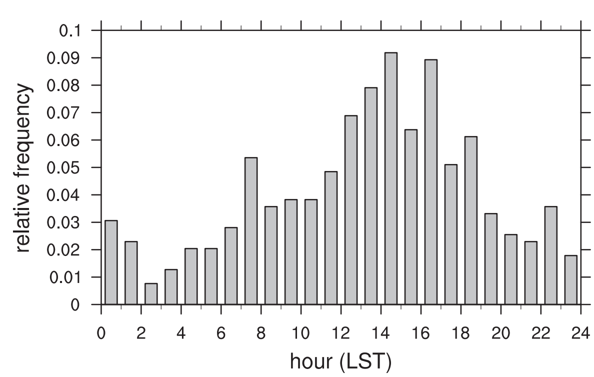

Fig. 5. Diurnal variation of hail occurrence.

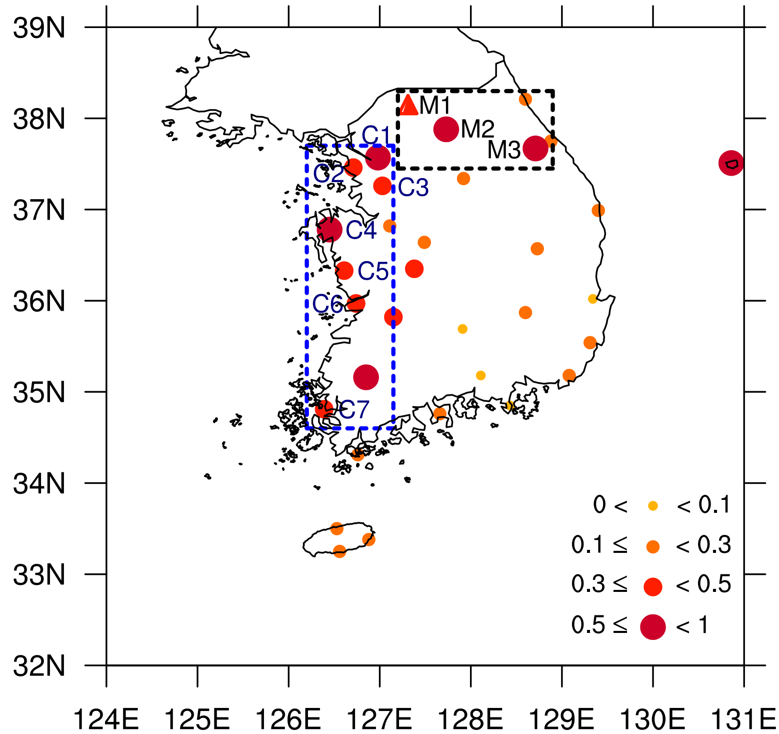

Fig. 6. Spatial distribution of annual-mean hail frequency. The blue box corresponds to the west coastal area, and the black box corresponds to the east mountainous area. 7 locations from C1 to C7 are the west coastal observatories, and 3 locations from M1 to M3 are the east mountainous observatories. The triangle (M1) is the observatory which started observation from 1987.

decreases, but the hail frequency at the east mountainous observatories exhibits their peak values. The hail days nearly disappear again throughout the country in July, August, and September. The hail days start to appear in October in the west coastal area, making November their peak month of hail occurrence.

As can be observed from the monthly variation of spatial distribution, the temporal features of hail occurrence of the two groups are different from each other. Fig. 8 shows the monthly-mean hail frequency for the two groups. The west coastal observatories have low peaks of hail frequency in spring and high peaks in November (Fig. 8a). In contrast, the east mountainous observatories have high peaks in May and low peaks in autumn (Fig. 8b). These results are similar to those for North Korea (Kim and Ni, 2015) which show a spring peak in the middle mountainous area and an autumn peak in the western plain area.

The large number of hail occurrence at the west coastal observatories in spring and late autumn in South Korea may be related to the water vapor transported from the Yellow Sea by westerly winds. In some regions of the world, the supply of water vapor from the adjacent sea affects strong convective precipitation (e.g., Vinet, 2001; Sioutas, 2011). Wu et al. (2016) examined intense convective systems along the southern Himalayan boundary and showed that the intense convective systems mainly occur under a condition of moderate low-level moisture but do not occur frequently under a too moist condition or under a too dry condition. They suggested that the atmospheric instability is usually released by relatively weak convection under a highly moist condition and a dry condition is not favorable for developing the intense convective systems. It is likely that moderate low-level moisture in spring and autumn transported by westerly winds from the Yellow Sea is related to the high hail frequency in the west coastal area of South Korea, but further studies are needed to confirm their relationship.

Mountainous terrain has often been reported to be related to high hail frequency (e.g., Changnon, 1977; Vinet, 2001; Zhang et al., 2008; Sioutas et al., 2009; Suwala and Bednorz, 2013). Mountains can divert flows and produce low-level convergence zones (Nisi et al., 2016). It is suggested that even small mountains or hills can influence the development of convective storms due to the convergence caused by horizontal and vertical flow deviations around them (Puskeiler et al., 2016). Mountainous terrain is likely to be related to the relatively high hail frequency at the east mountainous observatories neighbored by mountains. Reasons for the relatively low hail frequency in late autumn and the later first peak in the mountainous area compared with the west coastal area are not investigated yet, needing further research.

3.3. Relations to thermodynamic and dynamic factors

Hail occurs as a result of a combination of multiple factors (Vinet, 2001). The factors generally known to affect hail occurrence are topographical characteristics, sufficient low-level moisture supply, low freezing-level height, strong vertical wind shear, upper-level jet streams, cold fronts at low levels, and thermodynamic instability (e.g., Dessens, 1986; Vinet, 2001; Zhang et al., 2008). However, their relative importance with respect to hail occurrence is different from one region to another (Zhang et al., 2008). In this subsection, how thermodynamic and dynamic factors are related to hail occurrence in South Korea is analyzed. For this, the 700–500 hPa temperature lapse rate, mean water vapor mixing ratio in the lowest 100 hPa, CAPE, and 0–6 km bulk wind shear are considered.

First, the relationship between hail occurrence and the 700–500 hPa temperature lapse rate is examined. Since a large midlevel temperature lapse rate can cause the midlevel atmosphere to be unstable, it is one thermodynamic factor expected to offer a favorable environment for hail occurrence. Also, the midlevel temperature lapse rate can be an indicator of upper-level cold air advection or lower-level warm air advection, which decreases the stability of the atmosphere. The midlevel temperature lapse rate has been tested as one of the predictors of hail occurrence in many studies (Farnell and Llasat, 2013; Allen et al., 2015). A comparison of the relative frequency distributions of 700–500 hPa temperature lapse rate for hail days and all days is illustrated

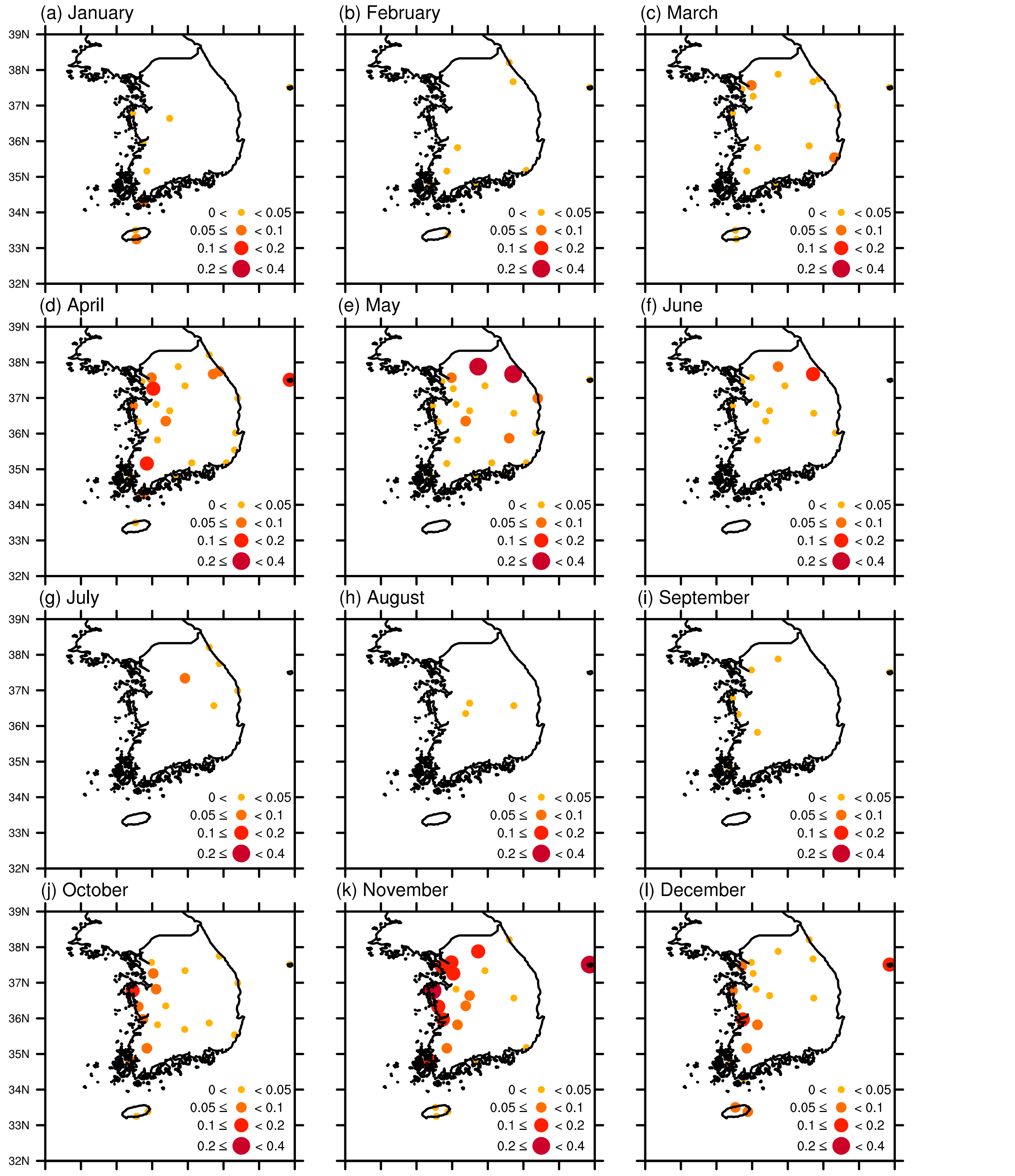

Fig. 7. Spatial distributions of monthly-mean hail frequency in (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December.

in Fig. 9a. The 700–500 hPa temperature lapse rate for hail days is calculated using the 54 atmospheric sounding data observed at the 7 stations. The 700–500 hPa temperature lapse rate for hail days is larger on average than that for all days. More than 85% of the whole hail days have temperature lapse rate larger than 5.5 K km^{-1}, suggesting that hail usually occurs in a condition with a large midlevel temperature lapse rate in South Korea.

Interestingly, the pattern of the monthly variation of 700–500 hPa temperature lapse rate for all days is similar to the monthly variation of monthly-mean hail frequency (Figs. 4 and 9b). Both have double

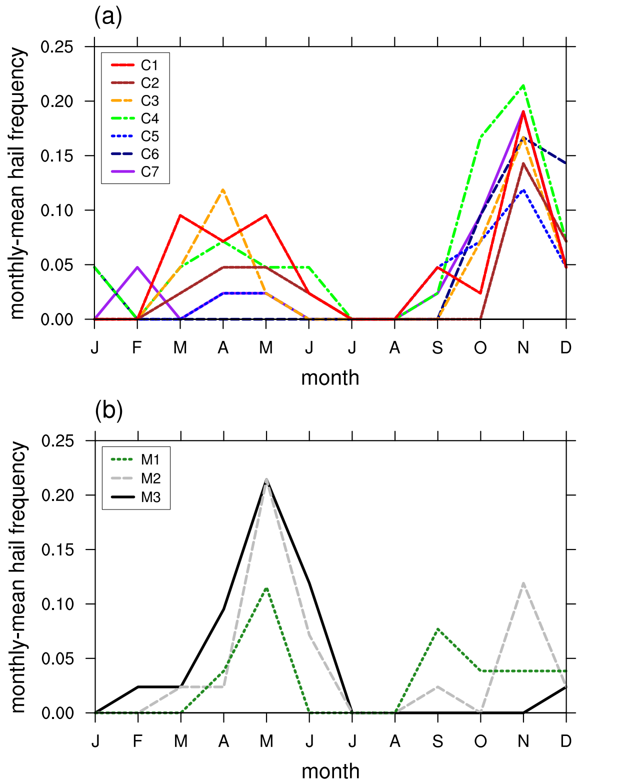

Fig. 8. Monthly variations of monthly-mean hail frequency at observatories in the (a) west coastal area and (b) east mountainous area.

peaks in spring and autumn (November) and small values in summer and winter. There is a strong correlation with the correlation coefficient of 0.89 (not shown). From this, the hail occurrence in South Korea can be said to be related to the 700–500 hPa temperature lapse rate. As a result, the reason why the monthly-mean hail frequency exhibits the double peak structure is partially explained by the monthly variation of midlevel temperature lapse rate.

The mean water vapor mixing ratio in the lowest 100 hPa is selected as a thermodynamic factor representing low-level moisture supply. Hail occurs when there exists sufficient moisture from which the hailstorm can obtain the required amount of liquid water (Longley and Thompson, 1965). The thermodynamic factors related to the moisture such as relative humidity and mixing ratio have been also used to find their relation to hail occurrence (Farnell and Llasat, 2013; Allen et al., 2015). The relative frequency distribution of the water vapor mixing ratio averaged in the lowest 100 hPa for hail days is compared with that for all days (Fig. 10a). Hail occurs when the water vapor mixing ratio is in the range of ~2–11 g kg^{-1}. 63% of hail occurrence is concentrated in the range of water vapor mixing ratio from ~3 to ~6 g kg^{-1}. Only one case has a very large water vapor mixing ratio, larger than ~11 g kg^{-1}, and there were no cases with very small water vapor mixing ratios, smaller than ~2 g kg^{-1}. This result suggests that a low-level water vapor mixing ratio that is larger than ~2 g kg^{-1} can be regarded as a condition for hail occurrence. The monthly variation of water vapor mixing ratio does not show a notable relation to the monthly variation of hail days (Figs. 4 and 10b). The water vapor mixing ratio has a high peak in summer, but the hail frequency is the lowest in summer. The low hail frequency in winter may be attributed to the lack of low-level moisture.

CAPE represents a quantity that is closely related to the environment where deep convection may occur (Doswell and Rasmussen, 1994). Therefore, CAPE has also been used in many studies as a thermodynamic factor associated with hail (Xie et al., 2008; Allen et al., 2015; Mohr et al.,

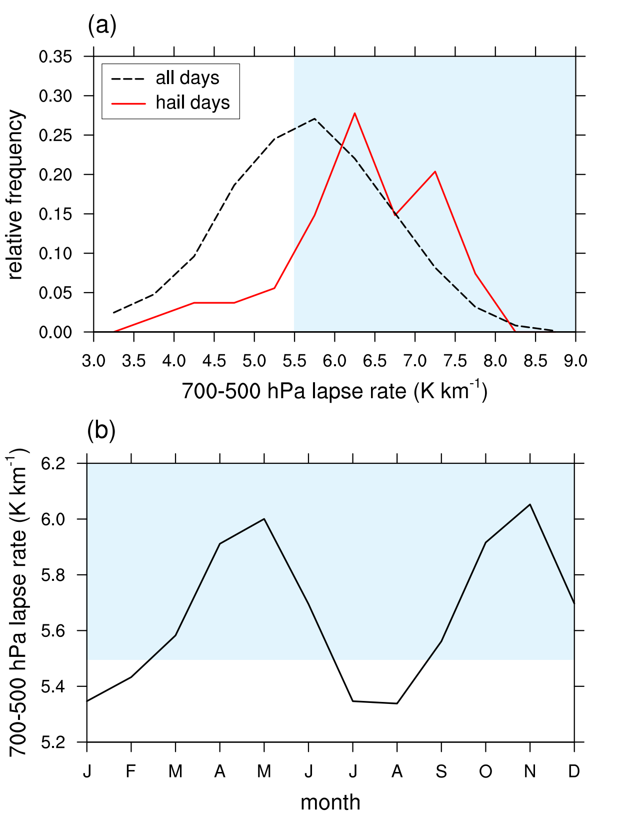

Fig. 9. (a) Relative frequency distributions of 700–500 hPa temperature lapse rate for hail days and all days. (b) Monthly variation of 700–500 hPa temperature lapse rate for all days. The ranges larger than 5.5 K km^{-1} covering 85% of hail occurrence are shaded.

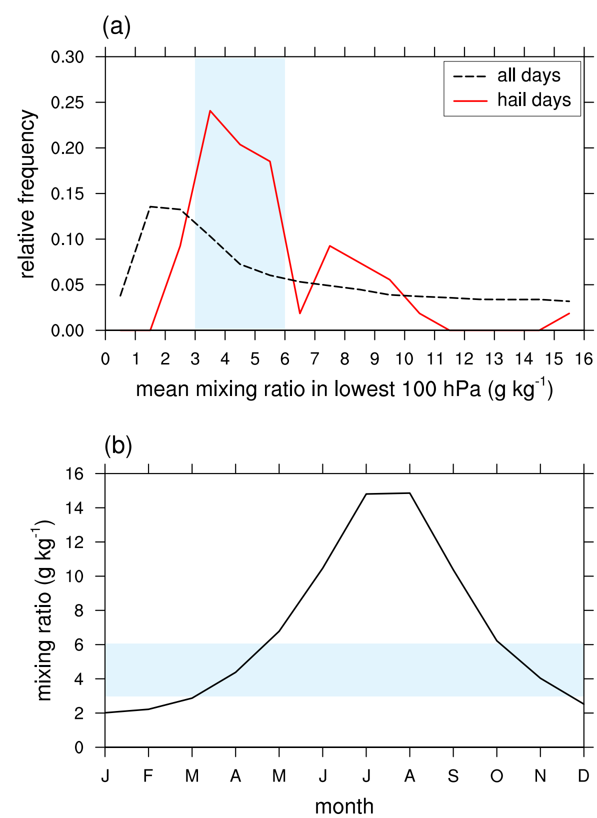

Fig. 10. As in Fig. 9 but for the mean water vapor mixing ratio in the lowest 100 hPa. The ranges of 3–6 g kg^{-1} covering 63% of hail occurrence are shaded.

2015). Although CAPE tends to be large when the midlevel temperature lapse rate is large, it is differentiated from the midlevel temperature lapse rate in that it is greatly affected by the near-surface temperature, low-level temperature lapse rate, and low-level humidity. The relative frequency distributions of CAPE for hail days and all days are also compared (Fig. 11a). CAPE for hail days appears to be larger on average than that for all days, but there are no hail events observed when CAPE is larger than ~300 J kg^{-1}. This means that in South Korea, it is difficult to find a distinct relationship between CAPE and hail occurrence. The monthly variation of CAPE also does not provide a good explanation for the monthly variation of hail days (Figs. 4 and 11b). CAPE shows a peak in summer whereas the hail frequency is the lowest in summer.

CAPE for hail days in South Korea appears to be relatively small compared to other regions such as the Netherlands (Groenemeijer and van Delden, 2007) and central Europe (Pucik et al., 2015). One possible reason for relatively small CAPE values is that the hail occurrence in South Korea is concentrated in spring and late autumn in which moderate CAPE is usually observed. Moreover, in some cases, relevant soundings are not close to the time of hail occurrence so CAPE values may be underestimated.

Bulk wind shear has been known as a factor that is related to the development of supercell storms (e.g., Weisman and Klemp, 1982; Bunkers et al., 2006). Because supercell storms can produce severe weather, the relation between the 0–6 km bulk wind shear and hail occurrence has been examined (e.g., Groenemeijer and van Delden, 2007; Pucik et al., 2015). The relative frequency distributions of 0–6 km bulk wind shear for hail days and all days are illustrated in Fig. 12a. It is clearly seen that the relative frequency of strong bulk wind shear is higher in hail days than in all days. The mean value of the bulk wind shear for hail days is much larger than that for all days. Therefore, the hail occurrence in South Korea is closely related to bulk wind shear. 79% of hail occurrence has bulk wind shear larger than 20 m s^{-1}. The major range of bulk wind shear for hail days varies depending on regions, but that in South Korea is large due to the relatively high hail frequency in spring and late autumn when bulk wind shear is not weak (Fig. 12b). The 0–6 km bulk wind shear is weak in summer. In summer, this weak bulk wind shear along with the small midlevel temperature lapse rate seems to contribute to the low hail frequency.

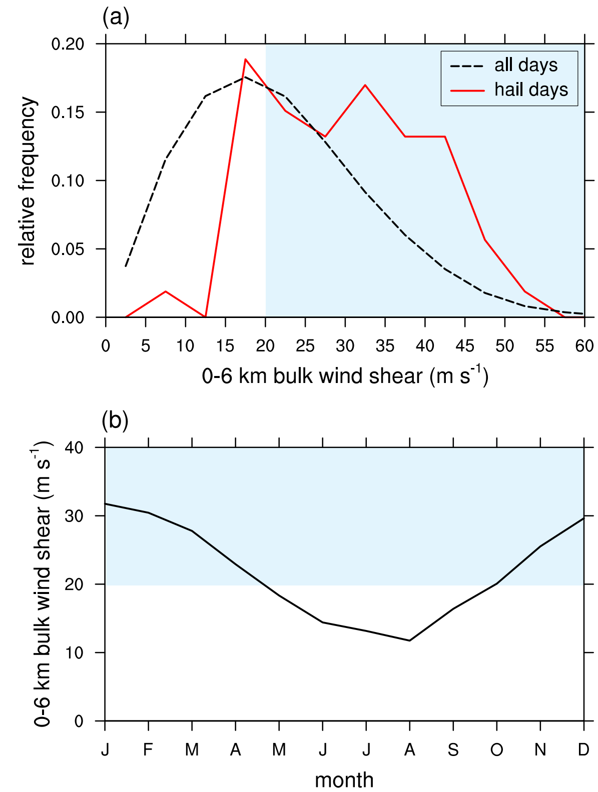

Fig. 12. As in Fig. 9 but for the 0–6 km bulk wind shear. The ranges larger than 20 m s^{-1} covering 79% of hail occurrence are shaded.

Among the analyzed factors, the 700–500 hPa temperature lapse rate and the 0–6 km bulk wind shear are shown to be related to the hail frequency. Since there is a strong negative trend in the number of annual hail days (Fig. 2), the annual trends of 700–500 hPa temperature lapse rate and 0–6 km bulk wind shear are examined (Fig. 13a and b). In Fig. 13a, it is difficult to find a distinct overall decreasing trend of annually averaged midlevel temperature lapse rate as seen in the annual variation of hail days although it has been decreasing since 2001. The correlation between the annual variation of 700–500 hPa temperature lapse rate and the annual variation of hail days is statistically insignificant at the significance level of 95%. On the other hand, the overall decreasing trend of 0–6 km bulk wind shear is notable, which is 0.7 m s^{-1} per decade (Fig. 13b). The correlation between the annual variation of bulk wind shear and the annual variation of hail days is statistically significant at the significance level of 95% with the correlation coefficient of 0.41.

In addition to the 700–500 hPa temperature lapse rate and the 0–6 km bulk wind shear, the annual trend of the freezing-level height is examined to find another possible reason for the annual decreasing trend of hail frequency. The increasing trend of freezing-level height is found in South Korea (Fig. 13c), suggesting that global warming could be related to the decreasing trend of hail days in South Korea. The freezing-level height has increased by 85 m per decade. The correlation coefficient between the annual variation of freezing-level height and that of hail days is 0.41. It is worth noting that in recent decades, the annual-mean temperature of the Korean Peninsula has increased at a higher rate than that averaged over the world (Hong et al., 2015). Relatively strong atmospheric warming compared to other countries might have more affected the hail frequency in South Korea.

It is noted that the decrease in bulk wind shear and the increase in freezing-level height can explain only a part of the decrease in hail

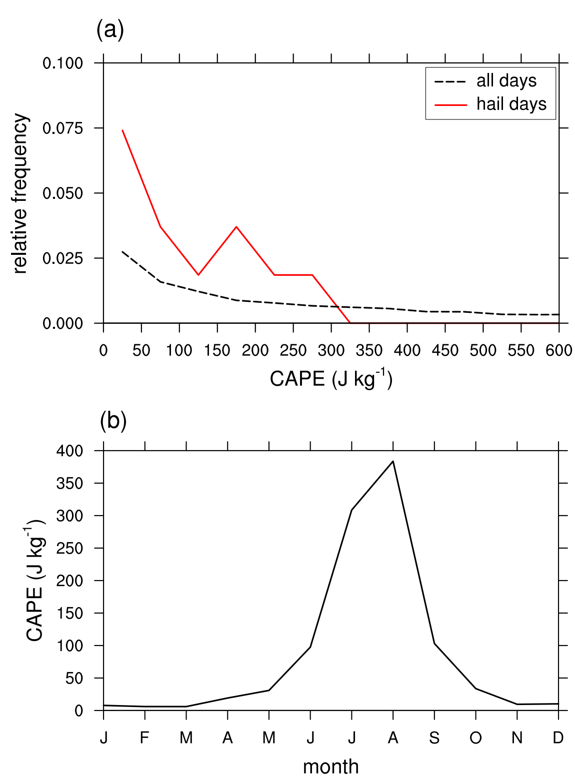

Fig. 11. As in Fig. 9 but for CAPE.

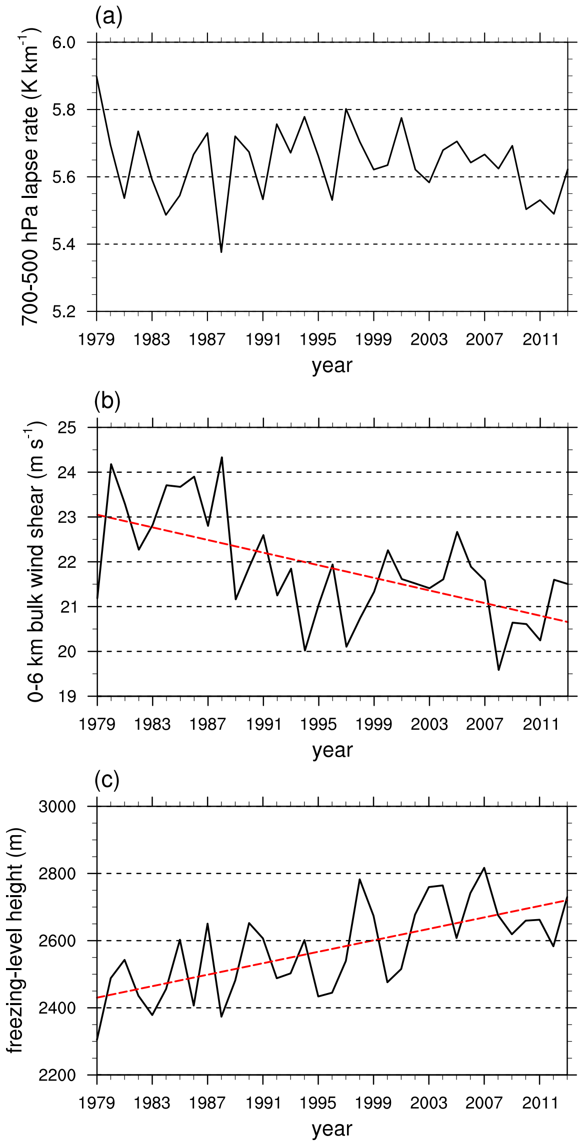

Fig. 13. Annual variations of (a) 700–500 hPa temperature lapse rate, (b) 0–6 km bulk wind shear, and (c) freezing-level height for all days and their linear trends. The equations of the trend lines in (b) and (c) are $y = -0.07(x - 2013) + 20.6$ ($R^2 = 0.36$) and $y = 8.5(x - 2013) + 2720$ ($R^2 = 0.45$), respectively. The annual trend of 700–500 hPa temperature lapse rate is statistically insignificant at the significance level of 95%.

days. The relative decrease in bulk wind shear for the period 1979–2013 is approximately 10%. The increase in freezing-level height for the same period is about 350 m. By examining the relationship between freezing-level height and the number of hailstones in each diameter range using hailpad network observation in southwestern France, Dessens et al. (2015) suggested that when the freezing-level height is increased by 500 m, the change in hailstone size distribution causes a decrease in the total number of hailstones by 12%.

In order to figure out whether the thermodynamic and dynamic factors that are analyzed in this study can explain the trend of annual hail days, the trend of the number of days that satisfy specific conditions of the factors in April, May, October, November, and December, in which the hail frequency is relatively high, is examined. The ranges of the thermodynamic and dynamic factors where their relative frequencies show large differences between hail days and all days, which are 700–500 hPa temperature lapse rate larger than 7.0 K km^{-1}, water vapor mixing ratio from 3 to 6 g kg^{-1}, bulk wind shear larger than 30 m s^{-1}, and freezing-level height lower than 2000 m, are selected for the conditions. The number of days satisfying these conditions in those months decreased by 54% in the 35 years (Fig. 14). This decreasing trend is statistically significant like the decrease of the number of annual hail days and may explain some features of the variation of annual hail days, e.g., the peak in 1992. However, it does not fully explain the fluctuations of annual hail days in the period. The correlation coefficient between the trend of the number of days satisfying the conditions and the trend of the annual hail days is 0.33, and the correlation is statistically significant at the significance level of 90% but insignificant at the significance level of 95%. Therefore, a large part of the decreasing trend of hail days in South Korea should be explained in further studies that consider the relationship between synoptic patterns or further thermodynamic and dynamic factors and hail occurrence.

In conclusion, the hail occurrence in South Korea is influenced most strongly by the midlevel temperature lapse rate and the bulk wind shear among the examined factors. In spring and autumn, the large midlevel temperature lapse rate related to the cold-air advection in the middle or upper level contributes to the formation of a favorable environment for hail occurrence. In summer, despite the sufficient low-level moisture supply and large CAPE, hail is rarely observed at the surface due to the high freezing-level height, the small midlevel temperature lapse rate, and the weak bulk wind shear. In winter, not only the midlevel temperature lapse rate is small but also the low-level moisture supply is not sufficient so that hailstorms form rarely. The overall negative trend of hail occurrence in South Korea is partly related to the annual decreasing trend of bulk wind shear and the annual increasing trend of freezing-level height. The number of days that have large midlevel temperature lapse rate, moderate water vapor mixing ratio, strong bulk wind shear, and low freezing-level height in the months with relatively high hail frequency is in a decreasing trend. However, these factors does not fully explain the fluctuations of hail occurrence, implying that other various factors would be related to the annual trend of hail occurrence.

Besides the factors examined in this study, various factors such as synoptic patterns are certainly related to hail occurrence in South Korea. Therefore, further studies using various factors and datasets such as reanalysis data can improve our understanding of hail climatology in South Korea.

4. Summary

Using a hail observation dataset for the period 1972–2013 provided by KMA, the temporal and spatial distributions of hail occurrence in South Korea were examined. The annual-mean hail frequency averaged over all observatories in South Korea is 0.29, and it is annually decreasing at a rate of 0.09 per decade. The monthly variation of hail days exhibits double peaks in April and November. Unlike many other areas in the world, the hail frequency in South Korea is low in summer. This

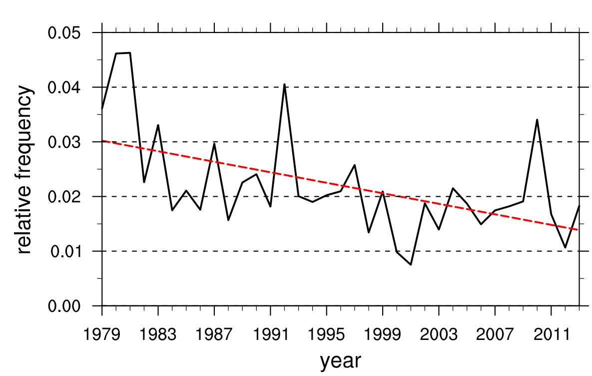

Fig. 14. Annual variation of the number of days in April, May, October, November, and December that have 700–500 hPa temperature lapse rate larger than 7.0 K km^{-1}, mean water vapor mixing ratio in the lowest 100 hPa from 3 to 6 g kg^{-1}, 0–6 km bulk wind shear larger than 30 m s^{-1}, and freezing-level height lower than 2000 m and its linear trend. The equation of the trend line is $y = -0.00048(x - 2013) + 0.014$ ($R^2 = 0.28$).

is likely to be related to the high freezing-level height, small midlevel temperature lapse rate, and weak bulk wind shear in summer. The occurrence time of hail is concentrated in the afternoon due to surface heating during the daytime. Spatially, hail primarily occurs in the west coastal area and the east mountainous area in South Korea, with different monthly distributions in the two areas. Among the factors considered, the 700–500 hPa temperature lapse rate shows the deepest relationship with the hail occurrence. In South Korea, hail is likely to occur in seasons when the midlevel temperature lapse rate is large, which are spring and autumn. The water vapor mixing ratio in the lowest 100 hPa is in a certain range for hail days. CAPE does not show a strong relationship with the hail occurrence. The relative frequency of strong bulk wind shear is higher in hail days than in all days. In spite of its deep relation to the monthly variation of hail occurrence, the annual variation of 700–500 hPa temperature lapse rate does not show a statistically significant relationship with the annually decreasing trend of hail occurrence in South Korea. Instead, the bulk wind shear is decreasing and the freezing-level height is increasing annually, which is related to the annually decreasing trend of hail occurrence in South Korea.

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References

Allen, J.T., Tippett, M.K., Sobel, A.H., 2015. An empirical model relating U.S. monthly hail occurrence to large-scale meteorological environment. J. Adv. Model. Earth Syst. 7, 226–243.
Brooks, H.E., Lee, J.W., Craven, J.P., 2003. The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. Atmos. Res. 67–68, 73–94.
Bunkers, M.J., Johnson, J.S., Czepyha, L.J., Grzywacz, J.M., Klimowski, B.A., Hjelmfelt, M.R., 2006. An observational examination of long-lived supercells. Part II: environmental conditions and forecasting. Weather Forecast. 21, 689–714.
Changnon, S.A., 1977. The scales of hail. J. Appl. Meteorol. 16, 626–648.
Changnon, S.A., Changnon, D., 2000. Long-term fluctuations in hail incidences in the United States. J. Clim. 13, 658–664.
Dessens, J., 1986. Hail in southwestern France. I: hailfall characteristics and hailstorm environment. J. Clim. Appl. Meteorol. 25, 35–47.
Dessens, J., Berthet, C., Sanchez, J.L., 2015. Change in hailstone size distributions with an increase in the melting level height. Atmos. Res. 158, 245–253.
Doswell III, C.A., Rasmussen, E.N., 1994. The effect of neglecting the virtual temperature correction on CAPE calculations. Weather Forecast. 9, 625–629.
Etkin, D., Brun, S.E., 1999. A note on Canada's hail climatology: 1977–1993. Int. J. Climatol. 19, 1357–1373.
Farnell, C., Llasat, M.C., 2013. Proposal of three thermodynamic variables to discriminate between storms associated with hail and storms with intense rainfall in Catalonia. Tethys 10, 25–34.
Foote, G.B., 1984. A study of hail growth utilizing observed storm condition. J. Clim. Appl. Meteorol. 23, 84–101.
Giaiotti, D., Nordio, S., Stel, F., 2003. The climatology of hail in the plain of Friuli Venezia Giulia. Atmos. Res. 67–68, 247–259.
Groenemeijer, P.H., van Delden, A., 2007. Sounding-derived parameters associated with large hail and tornadoes in the Netherlands. Atmos. Res. 83, 473–487.
Hermida, L., Sanchez, J.L., Lopez, L., Berthet, C., Dessens, J., Garcia-Ortega, E., Merino, A., 2013. Climatic trends in hail precipitation in France: spatial, altitudinal, and temporal variability. Sci. World J. 2013, 494971.
Hong, J.-H., Kim, S.-K., Kim, D.-G., Hong, S.-C., Lee, J.-B., Moon, K.J., Cha, J.-S., Hong, J.S., Ma, Y.-I., Kim, S.-Y., Jung, H.-C., Choi, Y.-E., 2015. Korean climate change assessment report 2014: climate change impact and adaptation. NIER Technical Summary, NIER-GP2014-161. National Institute of Environmental Research.
Kahraman, A., Tilev-Tanriover, S., Kadioglu, M., Schultz, D.M., Markowski, P.M., 2016. Severe hail climatology of Turkey. Mon. Weather Rev. 144, 337–346.
Kim, C., Ni, X., 2015. Climatology of hail in North Korea. Acta Sci. Nat. Univ. Pekin. 51, 437–443 (in Chinese with English abstract).
Kim, J.-W., Lee, S.-G., Lee, G.-D., Yu, J.-H., 2001. Statistical features of hail incidences in Gangwon-do region. Hail Researches of Gangneung Regional Meteorological Administration. Gangneung Regional Meteorological Administration, pp. 3–14 (in Korean).
Korosec, M., 2009. Case study: an isolated severe storm with giant hail hit Slovenian capital city Ljubljana on May 25th 2009. 11th Plinius Conference on Mediterranean Storms. European Geosciences Union, Barcelona, Spain.
Li, M., Zhang, Q., Zhang, F., 2016. Hail day frequency trends and associated atmospheric circulation patterns over China during 1960–2012. J. Clim. 29, 7027–7044.
Lim, E., Jung, Y.-S., Nam, J.-C., 2000. Characteristics of hail occurred in the Korea Peninsular. J. Korea Water Resour. Assoc. 33, 229–235 (in Korean with English abstract).
Longley, R.W., Thompson, C.E., 1965. A study of causes of hail. J. Appl. Meteorol. 4, 69–82.
Merino, A., Garcia-Ortega, E., Lopez, L., Sanchez, J.L., Guerrero-Higueras, A.M., 2013. Synoptic environment, mesoscale configurations and forecast parameters for hailstorms in Southwestern Europe. Atmos. Res. 122, 183–198.
Mezher, R.N., Doyle, M., Barros, V., 2012. Climatology of hail in Argentina. Atmos. Res. 114–115, 70–82.
Michaelides, S.C., Savvidou, K., Nicolaides, K.A., Orphanou, A., Photiou, G., Kannaouros, C., 2008. Synoptic, thermodynamic and agroeconomic aspects of severe hail events in Cyprus. Nat. Hazards Earth Syst. Sci. 8, 461–471.
Mohr, S., Kunz, M., Keuler, K., 2015. Development and application of a logistic model to estimate the past and future hail potential in Germany. J. Geophys. Res. Atmos. 120, 3939–3956.
Nisi, L., Martius, O., Hering, A., Kunz, M., Germann, U., 2016. Spatial and temporal distribution of hailstorms in the Alpine region: a long-term, high resolution, radar-based analysis. Q. J. R. Meteorol. Soc. 142, 1590–1604.
Pucik, T., Groenemeijer, P., Ryva, D., Kolar, M., 2015. Proximity soundings of severe and nonsevere thunderstorms in central Europe. Mon. Weather Rev. 143, 4805–4821.
Punge, H.J., Kunz, M., 2016. Hail observations and hailstorm characteristics in Europe: a review. Atmos. Res. 176, 159–184.
Puskeiler, M., Kunz, M., Schmidberger, M., 2016. Hail statistics for Germany derived from single-polarization radar data. Atmos. Res. 178–179, 459–470.
Sanchez, J.L., Gil-Robles, B., Dessens, J., Martin, E., Lopez, L., Marcos, J.L., Berthet, C., Fernandez, J.T., Garcia-Ortega, E., 2009. Characterization of hailstone size spectra in hailpad networks in France, Spain, and Argentina. Atmos. Res. 93, 641–654.
Schuster, S.S., Blong, R.J., Speer, M.S., 2005. A hail climatology of the Greater Sydney area and New South Wales, Australia. Int. J. Climatol. 25, 1633–1650.
Simeonov, P., Bocheva, L., Marinova, T., 2009. Severe convective storms phenomena occurrence during the warm half of the year in Bulgaria (1961–2006). Atmos. Res. 93, 498–505.
Sioutas, M., 2011. Hail occurrence in Greece. 6th European Conference on Severe Storms. European Severe Storms Laboratory, Palma de Mallorca, Spain.
Sioutas, M., Meaden, T., Webb, J.D.C., 2009. Hail frequency, distribution, and intensity in northern Greece. Atmos. Res. 93, 526–533.
Sohn, B.J., Ryu, G.-H., Song, H.-J., Ou, M.-L., 2013. Characteristic features of warm-type rain producing heavy rainfall over the Korean peninsula inferred from TRMM measurements. Mon. Weather Rev. 141, 3873–3887.
Suwala, K., Bednorz, E., 2013. Climatology of hail in Central Europe. Quaest. Geographicae 32, 99–110.
Tuovinen, J.P., Punkka, A.J., Rauhala, J., Hohti, H., Schultz, D.M., 2009. Climatology of severe hail in Finland: 1930–2006. Mon. Weather Rev. 137, 2238–2249.
Vinet, F., 2001. Climatology of hail in France. Atmos. Res. 56, 309–323.
Weisman, M.L., Klemp, J.B., 1982. The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. Mon. Weather Rev. 110, 504–520.
Wu, X., Qie, X., Yuan, T., Li, J., 2016. Meteorological regimes of the most intense convective systems along the Southern Himalayan Front. J. Clim. 29, 4383–4398.
Xie, B., Zhang, Q., Wang, Y., 2008. Trends in hail in China during 1960–2005. Geophys. Res. Lett. 35, L13801.
Zhang, C., Zhang, Q., Wang, Y., 2008. Climatology of hail in China: 1961–2005. J. Appl. Meteorol. Climatol. 47, 795–804.