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Climatology of warm season cold vortices in East Asia: 1979–2005

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With 7 Figures

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Summary

The cold vortex is a major high impact weather system in the northeast China in warm season (May–September). An analysis was made in this study to document the distribution, size, origin, temporal variations of cold vortices, and their influence on warm season rainfall and severe weather during 1979–2005 in East Asia using the 500-hPa geopotential height of NCEP/DOE reanalysis data and a station precipitation dataset of China. All statistics except for precipitation and severe weather are made for two regions. Region I (20–70° N, 70–160° E) covers a broad area comprising the northern China-Siberian region to the northwestern Pacific coast and region II (35–60° N, 115–145° E), which is within region I, covers the northeast China and its surrounding areas only. Region II is a cold vortex rich region with an annual frequency of occurrence of 4 to 7. Cold vortex events occurred in May and June have higher frequency, longer duration, and larger size than those in other months in warm season in both regions I and II. Cold vortex events in region II have longer average duration and larger size than those in region I. The annual frequency of cold vortex events displays an interannual variability. In general, it is lower in both El Niño and La Niña years than in neutral years. Cold vortices contribute significantly to the annual warm season rainfall in northeastern China. The precipitation caused by cold vortices in northeastern China in warm season can be over 100 mm per year, accounting for 20–60% of the total warm season precipitation. Moreover, about 53% (22.4%) of hailstorm (rainstorm) days were caused by cold vortices in warm season in northeastern China during 1979 to 2005.

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1. Introduction

The cold vortex and cutoff low (COL) are synonym in some literatures (Hsieh 1949; Matsumoto et al. 1982). They are isolated from westerly jet stream. In the American Meteorological Society (AMS) glossary, a COL is defined as a cold low that has grown out of a trough and becomes displaced out of the basic westerly current and lies equatorward of this current. Cold vortices and COLs are typically present in middle troposphere, but they can often be found at 200 hPa and sometimes they can extend their characteristics down to the surface (Nieto et al. 2005). COLs form more often in summer than in winter and their favored formation regions are: southern Europe to eastern Atlantic coast; the northern China-Siberian region to the northwestern Pacific coast; and the eastern Pacific (Bell and Bosart 1989; Kentarchos and Davies 1998; Nieto et al. 2005).

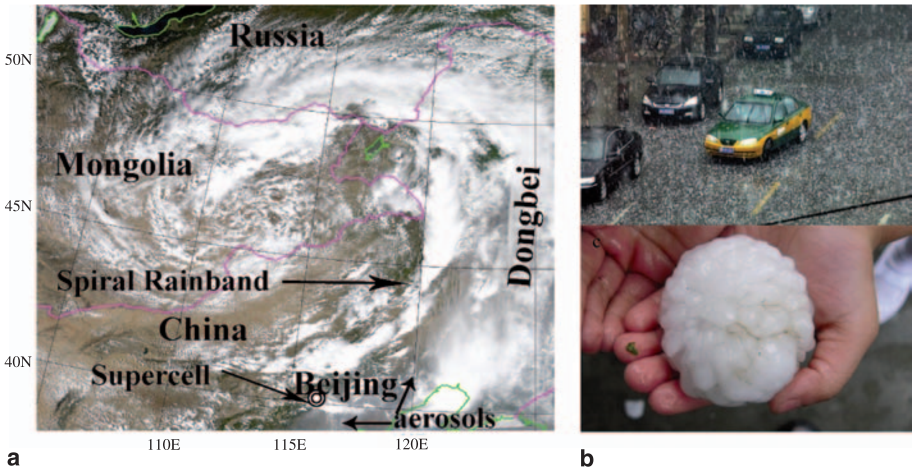


Fig. 1a. MODIS visible image of a cold vortex occurred in East Asia at 0530 UTC on May 31, 2005; (**b**) and (**c**) are street pictures when hail was occurring (after http://www.sina.com.cn)

COLs have been studied worldwide because they can cause severe weather and contribute to stratosphere-troposphere exchange (STE). As early as 1949, Hsieh (1949) conducted a case study for a selected cold vortex over North America, provided a detailed description of the formation and evolution of the cold vortex, and indicated a possible indirect circulation in the cold vortex. Palmén and Newton (1969) provided a dynamical characterization for COLs. Hoskins et al. (1985) presented a more robust description of COLs in terms of closed regions of high potential vorticity (PV) anomaly in the upper troposphere. COLs are often coupled with the tropopause folding, which could lead to the transfer of stratospheric air into the troposphere, thus playing a crucial rule in STE (Price and Vaughan 1993; Ancellet et al. 1994; Barsby and Diab 1995; Kentarchos and Davies 1998).

Cold vortices are associated with many significant forecasting problems in northern China, mainly due to their complicated dynamical structure and interaction with complex topography or other weather systems. They can lead to severe convective weather and cause floods to northeastern China, especially in late spring and early summer (Tao 1980; Zhao and Sun 2007). Figure 1 shows an example of a cold vortex, which formed on 31 May 2005 in East Asia. The Moderate Resolution Imaging Spectroradiometer (MODIS) visible image shows a complete picture of the cold vortex. A rainband spiraled anticylonically outward from the east to the south in the cold vortex. In the front of the spiral rainband, a supercell formed in the high aerosol area over Beijing city. The supercell and the following spiral rainband brought severe precipitation, hail, and strong winds to Beijing city and caused damage to buildings and transportation vehicles. Hails were observed 2 times during that day in Beijing city, one was caused by the supercell at noon (Fig. 1); the other was caused by the spiral rainband when it moved into Beijing city in the late afternoon.

Several previous studies on the Northern Hemisphere COLs climatology only provide a brief description of COLs in East Asia (Bell and Bosart 1989; Kentarchos and Davies 1998; Nieto et al. 2005). There have been few detailed studies on the regional climatology of COLs over East Asia as compared to other COLs regions, such as the Mediterranean (Llasat and Puigcerver 1990) and northeast United States (Novak et al. 2002). Moreover, there are some differences between the definition of COLs and cold vortices in China (Zheng 1992). These differences are similar to the differences between "cold air pools" and COLs in some European countries (Llasat et al. 2007). In Llasat's study, the concept of cold air pool places the emphasis on a depression borne upon a very cold-temperature nucleus, and in some cases the weak cold pools can arise out of a cold low when it fills up first at the surface and then survives for a further few days at high altitude, which occupied 9% of total cold air pools over the 1974–1983 period in Spain. In this study, a cold vortex is just defined as a depression with cold core at mid-upper troposphere, similar to the traditional definition (Zheng et al. 1992), which has more general meaning than COLs defined by AMS.

Although cold vortices in East Asia are a high impact weather system to the northeast China, their climatology has only been briefly discussed previously. The study of their climatology, undoubtedly, may provide a background for both research and forecast of cold vortices in the region. The purpose of this study is to conduct a detailed analysis for the spatial distribution and temporal variability of cold vortices in the northern China-Siberian region to the northwestern Pacific coast, with the special focus on the cold vortices in the area of 35–60° N, 115–145° E. The analysis is based on the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis. The data and method to pick out cold vortices from the NCEP reanalysis data are described in Sect. 2. The spatial distribution and temporal variability of cold vortices are presented in Sect. 3, which is followed by a discussion of cold-vortex-induced precipitation in Sect. 4. Conclusions are drawn in the last section.

2. Data and methodology

This study focuses on cold vortices occurred in East Asia and its surrounding areas (Fig. 2). region I (20–70° N, 70–160° E) almost covers east and northeast Asia; region II (35–60° N, 115–145° E) is a sub-region in Region I and is traditionally regarded as a productive area of cold vortices (Zheng et al. 1992). The analysis is carried out for the spring and summer months (April–September) for the period of 1979–2005, based on the NCEP/DOE AMIP-II reanalysis dataset which has a horizontal resolution of 2.5° longitudes/latitudes and time intervals of 6 hours (Ebisuzaki 1998; Kanamitsu 1999).

To pick out cold vortices as accurate as possible, a two-step algorithm is designed. The first step is fundamentally similar to that used in Bell and Bosart (1989). Based on the 500 hPa geopotential height at regular longitude/latitude grids for a specified geographical region, we first check grid point by grid point to determine whether the geopotential height is a minimum at a grid point. A grid point is considered as a height minimum only if it has the lowest geopotential height of the eight surrounding grid points and the height minimum is less than 5720 gpm. Once the height minimum is found, a test is performed to verify if an individual minimum is a cold vortex. To perform this test, the algorithm extends radial arms from the height minimum every 45° (for a total of 8 arms). Geopotential heights are interpolated every 76 km along each radial arm. If a 40 gpm height rise is detected in every direction before a height fall, then the height minimum is considered the center of a cold vortex. The radius of this cold vortex is the minimum distance of the eight arms.

The second step is to check whether the picked cold vortex would exist continuously in the fol-

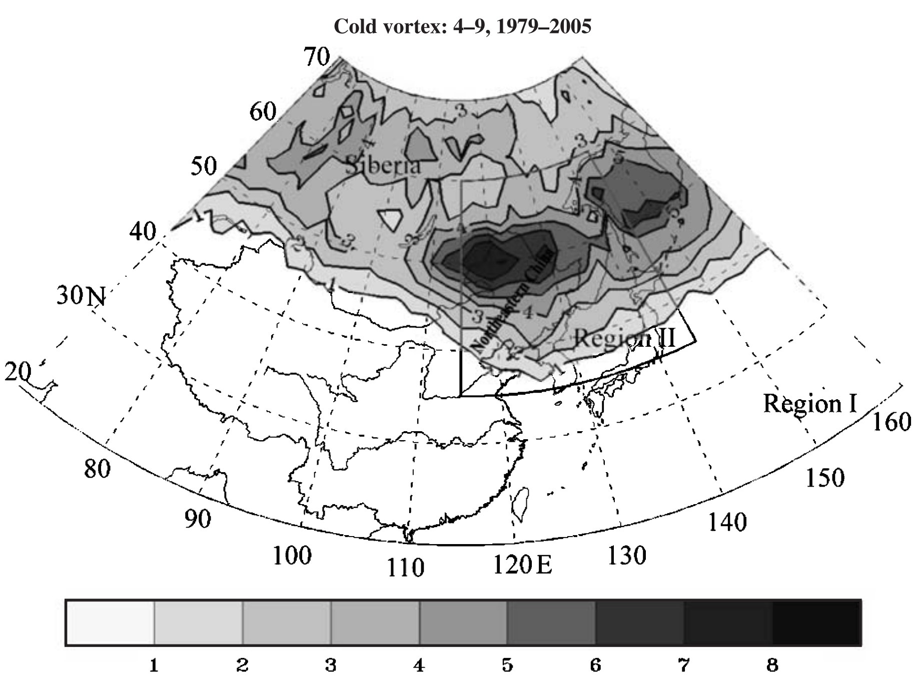


Fig. 2. Spatial distribution of the annual frequency of occurrence of cold vortices in warm season during 1979–2005. The annual frequency is plotted in 1 time interval. The area with annual frequency greater than 1 is shaded. The figure covers the region I with region II embedded as an inset

lowing time. After finding a cold vortex at an analysis time, a search will be carried out at the next 6 h to find if there exists a cold vortex within three grid points in all directions. If there does and the radial difference between the two cold vortices is no more than 500 km, they are regarded as the same cold vortex system. By using this algorithm, a cold vortex system can be tracked until it disappears. A cold vortex event is referred to as a cold vortex from its genesis to its dissipation.

The precipitation and hail data are offered by the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). This dataset includes precipitation and hail record for all weather stations in the surface meteorological observing network over the whole China from 1951 to 2005. The detailed description of this dataset can be found at www.nmic.gov.cn.

There are 164 and 132 stations that have precipitation and hail records, respectively, in northeastern China. A simple algorithm is designed to define the cold vortex precipitation. According to the center position and radius of each cold vortex defined above, the cold vortex influence area can be found as the area inside the radius of the cold vortex. The cold vortex precipitation of each station can be defined as the precipitation within the cold vortex influence area. A hailstorm day is defined as a day in which hail occurred in any time from 0000 UTC to next 0000 UTC for a station, while a rainstorm day is defined as a day the accumulated precipitation was more than 50 mm from 0000 UTC to next 0000 UTC for a station. A cold vortex hailstorm (rainstorm) day for each station is defined as the hailstorm (rainstorm) day when it was in the cold vortex influence area.

3. Spatial distribution and temporal variability of cold vortices

With the algorithms described in Sect. 2, 53,143 cold vortices are identified in region I with 6-hour intervals in summer season during the 1979–2005 period. Among them about 58.5% lasted less than one day, which are classified as short-lived cold vortex events, and thus are not considered in our statistics in this study. Only long-lived cold vortex events lasting more than one day are classified as cold vortex events hereafter. During the 27-year period, 3262 long-lived cold vortex events occurred over the region I, among them 1511 cold vortices entered or had their origin in region II. Note that few previous studies considered the continuity of COLs in their statistics (Kentarchos and Davies 1998; Nieto et al. 2005).

3.1 Frequency of occurrence

Figure 2 shows the annual frequency of occurrence of warm season cold vortices in both regions I and II. Obviously, high frequency mainly lies in the region of 45–55° N and 110–155° E, which we refer to as the cold vortex rich region. In the cold-vortex rich region, the annual frequency typically exceeds 4. In the west part of northeastern China and its surroundings, the annual cold-vortex frequency of occurrence exceeds 7. There are also some scattered high frequency centers in Siberia. Therefore, region II is a cold-vortex rich region. There is a secondary cold vortex rich region with the annual frequency of occurrence exceeding 5 to the east of region II over the Japan Sea in region I.

Note that although most cold vortices were centered in the northwest of region II, the rest of the region are highly influenced by the severe weather since cold vortices are synoptic weather systems. In general, severe weather, such high winds and heavy precipitation, occurs to the south, southeast and east quadrants in a cold vortex (Hsieh 1949; Palmén and Newton 1969; Nieto et al. 2005).

3.2 Genesis

The genesis of a cold vortex is defined in this study as the first time detected as a cold vortex by the algorithm described in Sect. 2. Although this is not a precise definition of genesis, it can give some insights into the climatology of the development of cold vortices. Figure 3 gives the spatial distribution of so-defined genesis location of cold vortices. The shaded area in Fig. 3 represents cold-vortex genesis events in region I. The symbols in Fig. 3 indicate the cold vortex events that entered region II or the cold vortex events with their origins in region II in summer season during 1979–2005.

The cold vortex genesis could occur almost everywhere north of 40° N. The area from the

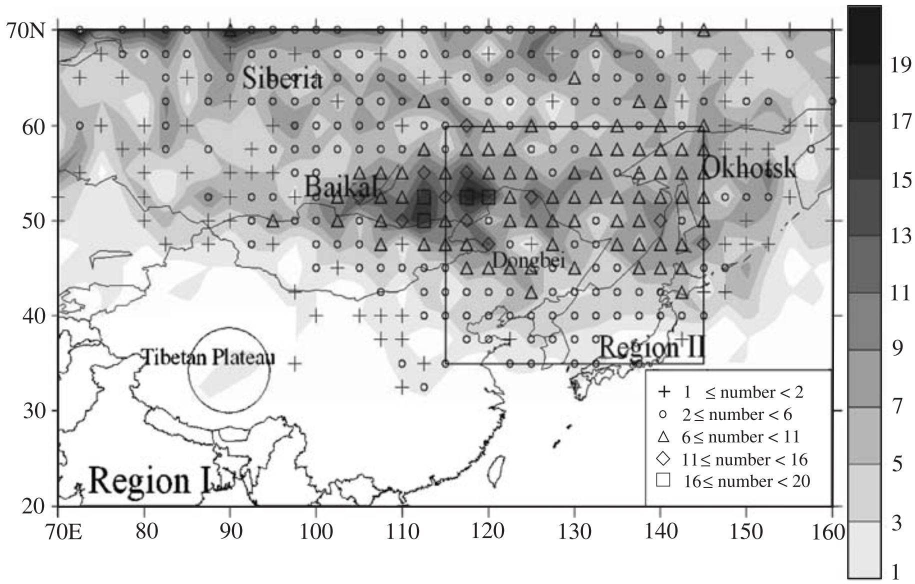


Fig. 3. Distribution of genesis location of cold vortices in summer season in East Asia during 1979–2005. The shading represents number of genesis in region I and the symbols stand for the numbers of cold vortices entered region II. The circle indicates the region where cold vortices originated over the Tibetan Plateau

east of Baikal to the west of northeastern China appears to be prone to the genesis of cold vortices. From Fig. 3, we can see that the west of region II is the key area for cold vortices to enter region II and a large portion of the cold vortices still had their locally origins in region II. There are some other areas where the cold vortices in region II had their origins. One is the area northeast to region II, indicating that the cold vortices moved southwestward or westward to enter region II. Another area is southwest to region II, indicating that the cold vortices in this area moved northeastward to enter region II.

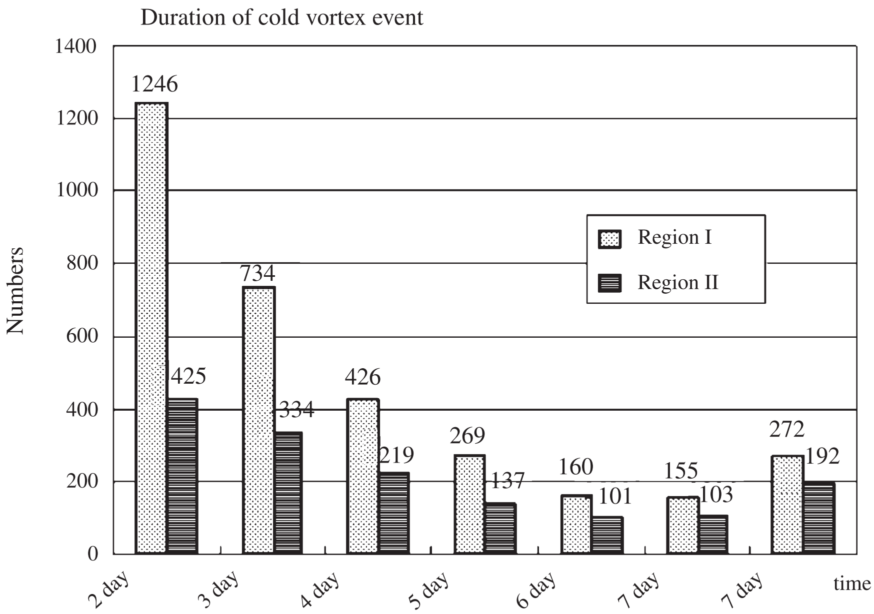
We should point out that our statistic method could not avoid counting some vortices in region II with their origins over the Tibetan Plateau (circled in Fig. 3). The vortices formed over the Tibetan Plateau seldom belong to COLs because they are mostly warm core cyclones and have different formation mechanism from cold vortices (Liu and Li 2006; Yu and Gao 2006). Such cyclones, if any, are just a very small portion of the total cold vortices detected in our statistics. Therefore, they should have little effect on our statistical results.

3.3 Duration and size

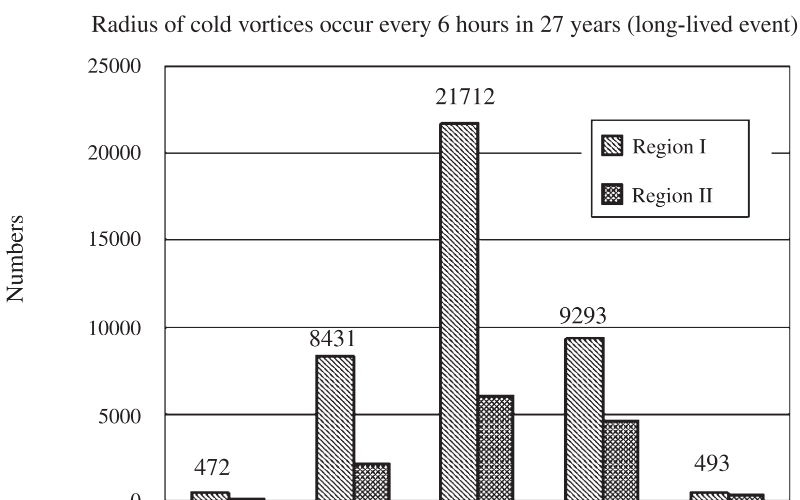
Figure 4 and Table 1 shows the statistics of duration of cold vortices and their radii in regions I and II, respectively. In region I, about 61% of cold vortex events lasted 2–3 days, 31% lasted 4–7 days, and only 8% lasted more than 7 days. The distribution of duration in region II is different from that in region I. In region II, only 50% of these events lasted 2–3 days, and near 37% lasted 4–7 days, and 13% lasted more than 7 days (Fig. 4a). It is obvious that the cold vortices that entered or originated in region II have longer duration than that in region I. The cold vortex size in region I presents a normal distribution with more than half of the cold vortices having radii between 600 and 900 km (Fig. 4b). On average, the cold vortices in region II have larger radii than that in region I. The long duration and large size in region II imply that cold vortices in this region would have significant impact on regional weather and climate.

3.4 Temporal variations

Table 2 shows the monthly variations of numbers of total cold vortices in region I and in region II, respectively. Cold vortices occurred much more often in the early summer, particularly in May and June, than other months in both regions. This is somewhat different from that in Europe and North America. In Europe, COLs mainly occur in both spring and summer (Llasat et al. 2007), while in North America, COLs occur in all seasons except for summer (Bell and Bosart 1989; Kentarchos and Davies 1998). Furthermore, on average, the cold vortices can last more than 90 hours in June, July and September in region I, while they can last more than 100 hours in June in region II.



a



	0–300	300–600	600–900	900–1200	≥1200
Region I	472	8431	21712	9293	493
Region II	139	2181	6032	4587	348

Radius (km)

b

Fig. 4. Statistics of duration of cold vortex events (**a**) and the radii of cold vortices (**b**) in regions I and II. The table under (**b**) lists the numbers of cold vortices with different radius range

Figure 5 shows the time series of the annual frequency of cold vortices in warm season in regions I and II, respectively. A slight downward linear trend can be found from 1979 to 2005, with a rate of -2 per decade. This decreasing trend could be an indication of the regional climate change and needs to be investigated in the future. The annual frequency also shows an interdecadal variation and prominent interannual fluctuations in both regions. The two highest frequencies of the cold vortices in region I occurred in 1995 and 2004, with the lowest frequency in 2002. In region II, the lowest and highest frequencies of the cold vortices events occurred in 1998 and 2004, respectively.

It is interesting to see whether there is any correlation between the variability of cold vortices and the El Nino/La Nila events. In Fig. 5, we

Table 1. Probability distribution of duration and radius of cold vortices in warm season during 1979–2005 in regions I and II, respectively

Duration	2 days	3 days	4 days	5 days	6 days	7 days	>7 days
Percentage (region I)	38.2	22.5	13.1	8.2	4.9	4.8	8.3
Percentage (region II)	28.1	22.1	14.4	9.1	6.7	6.8	12.7

Radius (km)	<300	300–600	600–900	900–1200	>1200
Percentage (region I)	1.1	20.9	53.7	23.0	1.2
Percentage (region II)	1.0	16.4	45.4	34.5	2.6

Table 2. Numbers of monthly cold vortices and monthly mean duration of cold vortex events in warm season during 1979–2005 in region I and region II, respectively

Month	April	May	June	July	August	September
Numbers in region I	6908	7524	7549	6278	5823	6301
Numbers in region II	2338	2674	2680	1765	1656	2172
Duration in region I	84.1	86.1	92.6	91.8	86.8	92.0
Duration in region II	87.2	90.1	102.1	90.6	82.1	87.8

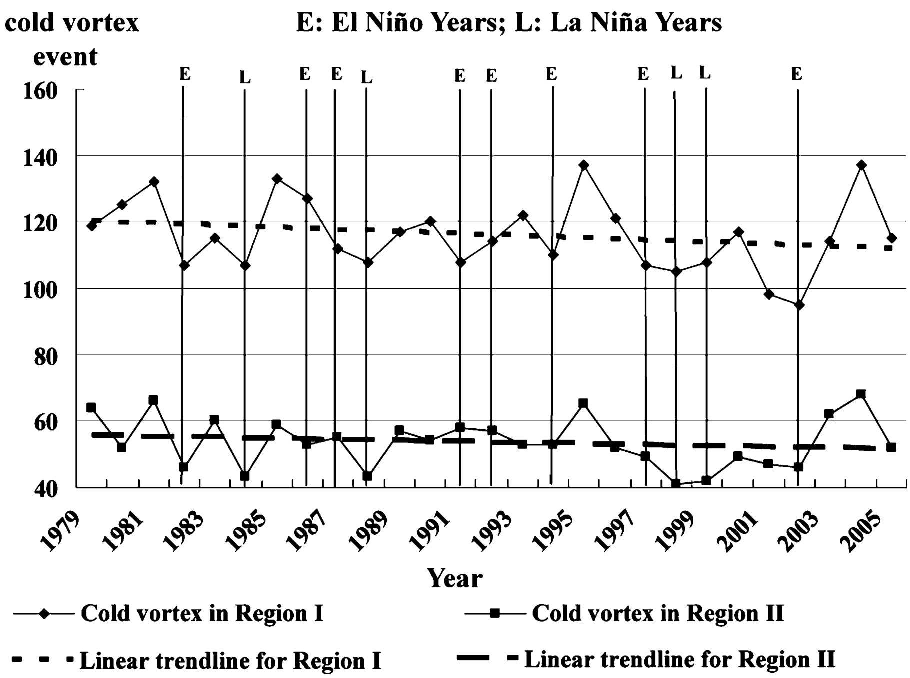


Fig. 5. Variations of annual cold vortex events in summer season during 1979–2005 in regions I and II. The dashed lines indicate the linear trends for both region I and region II. The vertical lines indicate the El Niño or La Niña years. "E" stands for "El Niño" and "L" stands for "La Niña". The El Niño or La Niña years are based on the data from CPC, CDC, WRCC and MEI

mark El Niño, La Niña and neutral years together with the variation of the annual frequency of cold vortices. We can see that an obvious above-normal frequency occurred in neutral years, such as 1981, 1984, 1989, 1994, 2004. Both in El Niño years and in La Niña years, cold vortex events are generally below average, especially in strong El Niño and strong La Niña years, such as 1982, 1988, 1991, 1997, etc. This is contrary to the results of Fuenzalida et al. (2005) who found that no correlation between the number of COLs and ENSO index for the Southern Hemisphere. However, why the cold vortex frequency is well below normal during the El Niño and La Niña years in East Asia is an open question and should be an interesting topic for a future study.

4. Influence on precipitation

Although it is well-known that cold vortices are major weather systems in East Asia, little is known how much regional precipitation is brought by cold vortices in warm season. Furthermore, so far there has been no comprehensive description of the influence of cold vortex events to severe weather systems, such as hailstorms and rainstorms. In this section, the results from a statistical analysis will be discussed with the focus on the climatological characteristics of precipitation associated with cold vortices in East Asia. The data we used include cold vortex information discussed already in Sect. 3 and the observed station precipitation data in northeastern China as described in Sect. 2.

Figure 6a shows the distribution of annual mean cold vortex precipitation in warm season during 1979–2005. Cold vortices mainly influence northeastern China. The annual cold vortex precipitation above 200 mm occurred to the east of 124° E and decreased rapidly southwesterward and became less than 50 mm in Hebei Province. The annual cold vortex precipitation was between 50 and 200 mm in Shandong, Hebei, Liaoning Provinces, and western part of Inner Mongolia. Since most cold vortices occurred frequently in the west of region II, the distribution of cold vortex-induced precipitation thus is consistent with previous results of Hiseh (1949), Palmĕn and Newton (1969), and Nieto et al. (2005), who found that severer weather generally occurs to the south, southeast, and east quadrants in a cold vortex.

Figure 6b gives the spatial distribution of the ratio of the cold vortex-induced precipitation to the total warm season precipitation during 1979–2005 at each station. It is obvious that the contribution by the cold vortex-induced precipitation to the total precipitation increases quickly poleward from Hebei Province to Heilongjiang Province. In Beijing city, Tianjin city and Hebei Province, cold vortices contribute more than 10% precipitation to the total precipitation with 20–30% in the most northern part of Hebei Province. The cold vortex-induced precipitation accounts for 30–40% of the total precipitation in Liaoning Province. For the areas north of 46° N, the contribution to the total precipitation by cold vortices can be over 50%. Since the summer precipitation in the region explains large portion of the annual precipitation, the result therefore indicates that cold vortices play a critical role in the regional climate.

Figure 7 shows the ratios of hailstorm days and rainstorm days associated with cold vortices to the corresponding annual accounts, respectively, at each station during 1979–2005. The pentacle means few hailstorms or rainstorms occurred for these stations during 1979–2005 (namely, less than 5 cases in 27 years). Obviously, cold

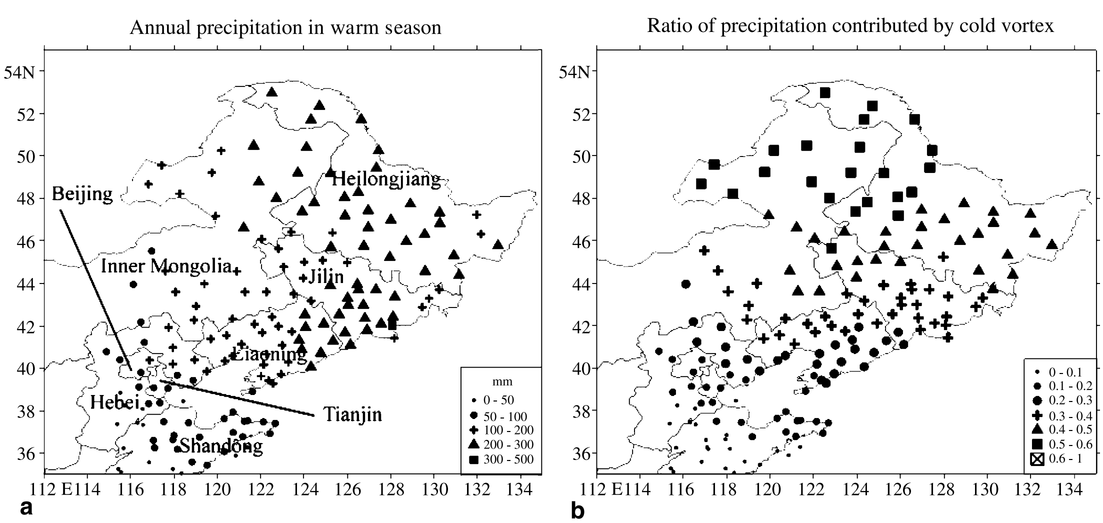


Fig. 6a. Annual mean precipitation associated with cold vortices and (**b**) the ratio of the annual mean precipitation associated with cold vortices to the total annual mean precipitation in warm season during 1979–2005 at all stations in northeastern China

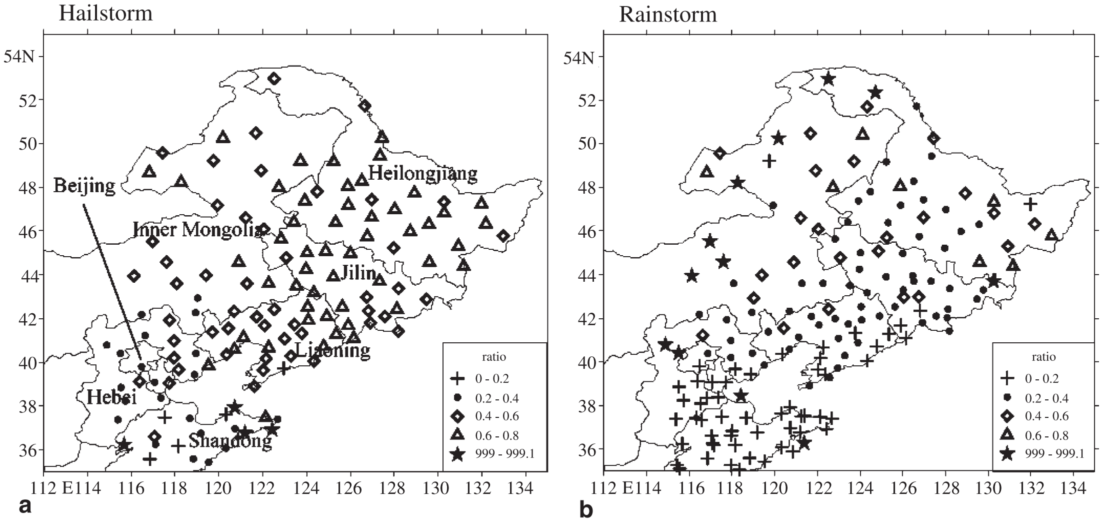


Fig. 7. The ratios of hailstorms (**a**) and rainstorms (**b**) caused by cold vortices to the corresponding total hailstorms and rainstorms, respectively, in warm season during 1979–2005 at all stations in northeastern China. The pentacle means few hailstorms or rainstorms occured for these stations during 1979–2005 (namely, less than 5 cases in 27 years)

Table 3. The hailstorms (**a**) and rainstorms (**b**) statistics averaged all stations in each month in warm season during 1979–2005 in northeastern China

Month	April	May	June	July	August	September	Total
a) Hailstorm							
Hailstorm days	272	960	1351	664	454	606	4307
Hailstorm days caused by cold vortex	134	601	802	304	160	280	2281
Percentage	49.3	62.6	59.4	45.8	35.2	46.2	53.0
b) Rainstorm							
Rainstorm days	70	126	644	2093	1715	367	5015
Rainstorm days caused by cold vortex	6	29	334	408	261	84	1122
Percentage	8.6	23.0	51.9	19.5	15.2	22.9	22.4

vortex hailstorm days in Hebei Province account for less than 40% of the annual hailstorm days, with some stations for about 10–20%. In northern China, cold vortex hailstorm days accounts for more than 40% of the annual hailstorm days, especially with more than 60% hailstorm days in Inner Mongolia and Heilongjiang and Jilin Provinces. The ratio of the cold vortex-induced rainstorm days to the annual rainstorm days has a spatial distribution very similar to that of hailstorm days except that the ratio is about 20% lower in most areas (Fig. 7b).

Table 3 summarizes the monthly statistics for the area averaged hailstorm and rainstorm days at all stations in northeastern China during 1979–2005. About 53% of hailstorm days were caused by cold vortices for the whole region in northeastern China, but only 22% of rainstorm days were caused by cold vortices in the same region. There are more hailstorm days in May and June than in other months. Most of hailstorm days in May and June are cold vortex-related, namely, accounting for 62.6% and 59.4% of the total hailstorm days in May and June, respectively. This result is consistent with the fact that May and June are cold vortex rich months compared to other months. The rainstorm days peak in July and August, but high ratio of cold vortex-induced rainstorm days appears in May, June, and September. This is mainly because rainstorms may be caused by both summer monsoon and landfalling tropical cyclones in addition to the cold vortices in summer in the region (Tao 1980; Zheng et al. 1992). Nevertheless, the above results indicate that cold vortices not only contribute significantly to the warm season precipitation but also to the severe weather events, such as hailstorms and rainstorms, in northeastern China.

5. Conclusions

East Asia is a cold vortex rich area according to some previous studies (Bell and Bosart 1989; Kentarchos and Davies 1998; Nieto et al. 2005). The cold vortex is a high impact weather system for the northeast of China. In this study, an analysis was conducted to document the climatology of cold vortices during 1979 and 2005 in the region covering the northern China-Siberian to the northwestern Pacific coast. The 500 hPa geopotential height from the NCEP/DOE reanalysis was used to identify the cold vortices with the use of a simple algorithm, which allows us to characterize the cold vortices, including their spatial distribution, frequency, genesis, duration and size, monthly and interannual variations, as well as their contributions to regional precipitation and severe weather events. Statistical analysis was made for two regions: region I (20–70° N, 70–160° E) covers a broad area, comprising the China-Siberian region to the northwestern Pacific coast and region II (35–60° N, 115–145° E) is inside of region I and covers the northeast of China and its surrounding areas only.

The east of Baikal to the west of the northeast China is a high frequency area of cold vortex genesis. Cold vortices form more often in May and June than in other months in warm season in East Asia. Region II is a region favorable for the formation of cold vortices. About 46% cold vortices formed in region I can influence region II. About 61% cold vortices in region I last 2–3 days and 9% can last more than 7 days. In region II, about half of cold vortices last 2–3 days, and 13% last more than 7 days. Cold vortex events in region II last longer than other areas in region I during April, May, and June. The majority of cold vortices in region I are found to have radii between 600 and 900 km, while cold vortices in region II have their radii between 900 and 1200 km, larger than those in region I. We also found that less cold vortex events occur in both El Niño years and La Niña years than that in neutral years and a decreasing trend in cold vortex events in both regions I and II during 1979–2005. However, the physical mechanisms responsible for the trend and variability are yet to be investigated in the future.

The possible influence of cold vortices on precipitation is also analyzed using cold vortex information, precipitation data from 164 observation stations and hail data from 132 stations in the northeast China. The results show that in northeastern China, cold vortex accounts for 20–60% of the total precipitation in summer. About 53% (22.4%) of hailstorm (rainstorm) days are caused by cold vortices in warm season during 1979–2005. Therefore, cold vortices play an important role in shaping the regional climate in northeastern China.

Acknowledgments

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