

Seasonal climatology of cut-off lows and associated precipitation patterns over Northeast China

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Abstract Cut-off lows (COLs) are significantly associated with many convective events and anomalous regional climate in the Northeast China. By using 49-year NCEP/NCAR reanalysis data, COL events are detected and tracked by an objective and automatic method based on synoptic concept model. Based on this dataset and daily rain-gauge records in Northeast China during 1979–2005, seasonal climatology of COLs and associated precipitation patterns over Northeast China are investigated. Most COLs have a short lifetime of less than a week and have a spatial size ranging from 500 to 1,000 km, with slight seasonal differences. Temporal variation of COL occurrence exhibits a seasonal cycle, with a peak in summer, and considerable interannual variability. The COLs tend to occur more frequently over the northern Northeast China Plain, and the center for maximum frequency shows a zonal oscillation, with an extension to continent in summer and a shift to western North Pacific coast in winter. Most COLs form to the east of Lake Baikal and decay over the western North Pacific coast. COLs are apt to move along east or southeast passages around the year, and tracks are relatively more complicated in warm seasons. About a quarter of annual mean precipitation over Northeast China is associated with COLs. Moreover, COL-associated

precipitation contributes greatly to total precipitation in northern and northwestern parts of Northeast China, and the ratios of COL contribution are stronger during spring and autumn than in summer.

1 Introduction

When a weak cold trough extends equatorward during the development of planetary waves in the westerlies, its connection to polar source can be cut off by warm air masses from lower latitudes, and then a closed cyclonic eddy, so called cut-off low (COL), may form to the south of main belt of zonally averaged westerlies (Palmen and Newton 1969). COLs are typically displayed as closed geopotential lows with cold core or cold trough in the middle and upper troposphere, which can persist for a few days until being destroyed by diabatic heating or friction (Hoskins et al. 1985).

The troposphere under COLs is generally highly unstable. When favorable surface conditions are satisfied, severe convective events can probably occur. Due to its slow movement, COLs can persist for several days and lead to moderate to heavy rainfalls over local areas (e.g., Qi et al. 1999; Campetella and Possia 2007). For example, in the summer of 1998, severe floods by persistent heavy rainfall in the valley of Songhuajiang River and Nenjiang River of Northeast China are closely related to long-term continually anomalous activities of COLs (Zhang et al. 2001; Zhao and Sun 2007). Accurate quantitative precipitation forecasting (QPF) under COLs is still a challenge in operational meteorology (Wang et al. 2007). Moreover, despite its short lifetime, the accumulative activities of COLs can affect regional climate over local and even remote regions (Zheng et al. 1992; He et al. 2007). COLs also play an important role

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in stratosphere–troposphere exchange (STE) (e.g., Vaughan and Price 1989; Baray et al. 2003). As lower tropopause with COL, tropopause fold is in favor of trace gases transportation from stratosphere to troposphere. Chemical effects by STE, especially ozone anomalies, can affect tropospheric radiation flux balance in reverse. STE associated with COLs is a key factor to tropospheric ozone anomaly in mid-latitude region (Kentarchos and Davies 1998).

Several studies on COLs have been undertaken on climatological analysis in the northern hemisphere (Bell and Bosart 1989; Price and Vaughan 1992; Kentarchos and Davies 1998; Nieto et al. 2005, 2008). With different data and methods, all these results show that Northeast China–Siberia is one of the most preferred regions of COL's occurrence. It is notable that COL has also been known as upper cold low, low vortex, and cold vortex, particularly in Northeast Asia (Sakamoto and Takahashi 2005). However, most previous studies have focused on the COL's frequency and favored occurrence regions, paying less attention to the other characteristics such as duration, genesis and lysis area, favorable tracks and associated convection distribution.

Most previous studies on COLs over Northeast Asia focused on the mesoscale features of individual cases and associated rainfall (Matsumoto et al. 1982; Chen et al. 1988, 2005), but paid less attention to the climatic aspects of COLs. Tao (1980) summarized vortex systems related to heavy rainfalls over China and emphasized effects of atmospheric anomalies on evolution of COLs over Northeast Asia. Some other studies investigated the statistical characteristics of COLs over Northeast Asia. Based on manual analysis of 25-year (1956–1980) daily weather charts, Zheng et al. (1992) performed a statistical analysis on COL over Northeast China. Sun et al. (1994) performed a study similar to Zheng et al. (1992) except for a longer period. These studies performed manual analyses of daily weather charts, which are painstaking and with considerable subjectivity (Gimeno et al. 2007).

Recently, Zhang et al. (2008) adopted an objective method similar to Bell and Bosart (1989), and examined the characteristics of COLs over Northeast Asia and COL's influence on precipitation over the area inside the radius of the COL, focusing only on warm season (May–September). It is likely that COLs can contribute relatively more to total seasonal rainfalls during cold seasons than warm seasons, since rainfalls in warm seasons over Northeast China are more affected by East Asia Summer Monsoon (EASM), particularly in July and August (Zheng et al. 1992; Wang et al. 2007). However, to our knowledge, none of previous studies have paid attention to seasonal differences. In addition, the circulation anomalies associated with COLs may affect weather condition not only at local, but also in remote areas (Zheng et al. 1992; He et al. 2007). Therefore,

to obtain the precipitation patterns associated with COL, one should examine precipitation anomalies over an area much wider than the circle with the radius of COL.

In this study, to facilitate the comparison with the results of Zhang et al. (2008), we adopt an objective analysis technique based on the conceptual model. Actually, there have been different methods to identify the COLs, including that based on isentropic potential vorticity (IPV) analysis (Wernli and Sprenger 2007). Similar results are identified by using these methods (Nieto et al. 2008). We construct a long-term dataset of COLs over Northeast Asia, and investigate the characteristics of COLs such as duration, size and frequency of occurrences. Moreover, seasonal differences about genesis and lysis areas, favorable tracks and precipitation patterns associated with COLs are also examined. The present method can also be used to assess abilities of climate models in simulating the climatological features of COLs.

In the present study, we focus on seasonal climatology of COLs and associated precipitation patterns over Northeast China. The data and method used are present in Sect. 2. Section 3 shows the seasonal characteristics of COLs. In Sect. 4, we show the seasonal differences in precipitation associated with COL. Finally, a conclusion is given in Sect. 5.

2 Data and methodology

In the present study, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996; Kistler et al. 2001) are utilized to perform an objective analysis on the climatology of COLs for a 49-year period from 1958 to 2006. Since typical size of COLs in northern hemisphere lies in the range of 600–1,200 km (Kentarchos and Davies 1998), it is reasonable that they can be detectable in this dataset with $2.5^\circ \times 2.5^\circ$ horizontal resolution. In addition, it is believed that 6-h data are relatively more objective and effective to detect and track extra-tropical cyclones than lower temporal resolution data (Blender and Schubert 2000).

Similar to the synoptic definition of COL by Zheng et al. (1992), we detect and track a COL event as: (1) closed low pressure located in the region range, 100° – 150° E, 30° – 65° N at 500 hPa isobaric surface; (2) cold core or evident cold trough accompanying with the above-mentioned low pressure. It should be noted that in the present study, we have extended the study region and lowered the bottom limit of duration in order to detect and track COLs as accurately as possible.

To quantify the definition of COL on grid dataset operationally, a three-step algorithm based on above definition is designed as below (Fig. 1).

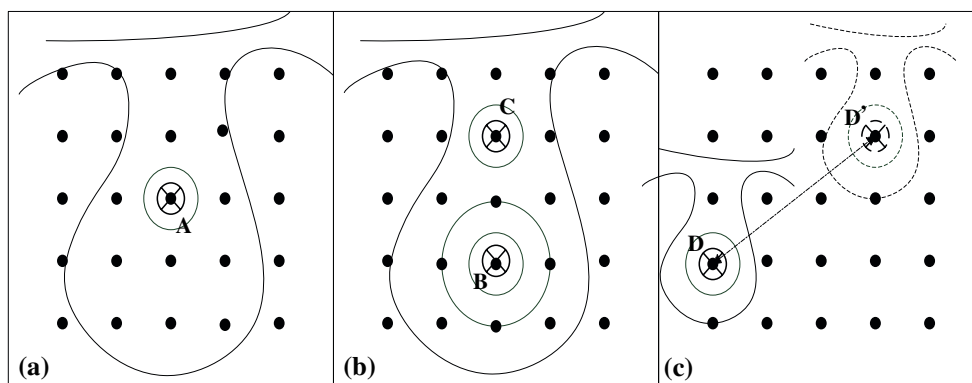


Fig. 1 Schematic representation of the objective method used to detect and track COLs event from grid-point dataset. *Solid lines* and *solid dots* denote geopotential height contour at 500 hPa at a given time t and grid points with $2.5^\circ \times 2.5^\circ$ resolution, respectively. *Long-dashed lines* denote geopotential height contour at 500 hPa at next

time $t + dt$ ($dt = 6$ h). *Dot-dashed arrow* denotes moving distance of COL at two consecutive times. **a**, **b** and **c** describe “detect”, “merge” and “track” algorithm of 3-step method, respectively. *A*, *B*, *C*, *D* and *D'* denote grid points satisfied with certain terms for each step, namely, potential centers of COL

(a) Detection algorithm

At the 500-hPa level for the specified region, a grid is considered as minimum if geopotential height is the lower than that of the surrounding eight grid points (*A* in Fig. 1a). Then, the minimum can be regarded as potential COL grid if any of the nine grid points in the box has positive zonal temperature Laplacian, e.g., $\frac{\partial^2 T}{\partial x^2} > 0$ (T denotes air temperature at the 500-hPa level).

(b) Merger algorithm

At any certain time, we regard the grid points fitted above criteria as the same system when they are in the same 5×5 grid box (*B* and *C* in Fig. 1b), and consider the grid point with lower geopotential height value as the main center of system (*B* in Fig. 1b).

(c) Track algorithm

At any two consecutive times (6 h), two detected grids above are viewed as the same system (*D* and *D'* in Fig. 1c) only if speed of movement is less than $10 \text{ dol}/6 \text{ h}$ ($\text{dol} = \text{degree of longitude}$). Otherwise, they belong to two independent systems.

We have redone the above detection, but by using the isobaric surfaces of 300 and 200 hPa, respectively, and found similar results. Since one of the main motivations of this study is to investigate precipitation distribution associated with COLs, and since the Chinese weather forecasters are used to predicting weather by using charts at 500 hPa, we adopt 500 hPa to detect COLs, rather than higher levels which may be more appropriate when studying other topics such as STE.

Despite lack of available statistical data by previous subjective analysis, a comparison was also performed to check between our results of objective analysis and 23-year (1958–1980) historical statistical result from manual

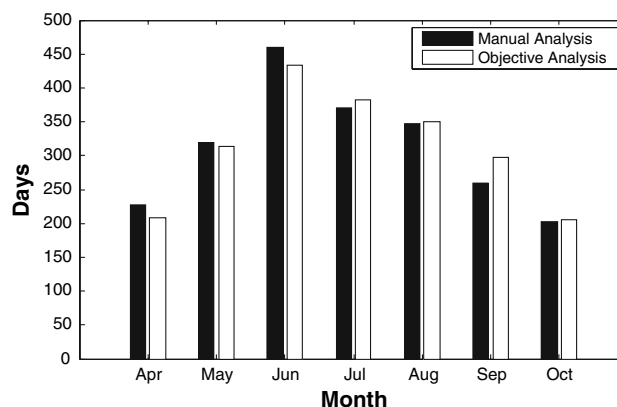


Fig. 2 Comparison of 23-year (1958–1980) monthly total COL days between manual analysis and objective result

analysis by Zheng et al. (1992) (Fig. 2). In this comparison, it should be noted that results from objective analysis are based on the region and duration threshold same as Zheng et al. (1992), i.e., the region of $115^\circ\text{--}145^\circ\text{E}$, $35^\circ\text{--}60^\circ\text{N}$, and duration threshold of 3 days. On monthly mean distribution of frequency, objective result agrees well with the feature by manual analysis. Concerning inter-annual variation of frequency between two methods' results, two time series have a correlation coefficient of 0.505 at the 95% significance level. For a random selected season (summer in 2007), we also have compared the outputs by objective tracking with manually analyzed cases from historical weather charts provided by National Meteorological Center (NMC), China Meteorological Administration (CMA), and on the whole the two show a good consistency.

To investigate seasonal precipitations associated with COLs, daily rain-gauge records during 1979–2005 at the stations covering Northeast China are analyzed. The rain-gauge data were obtained from the National Meteorological

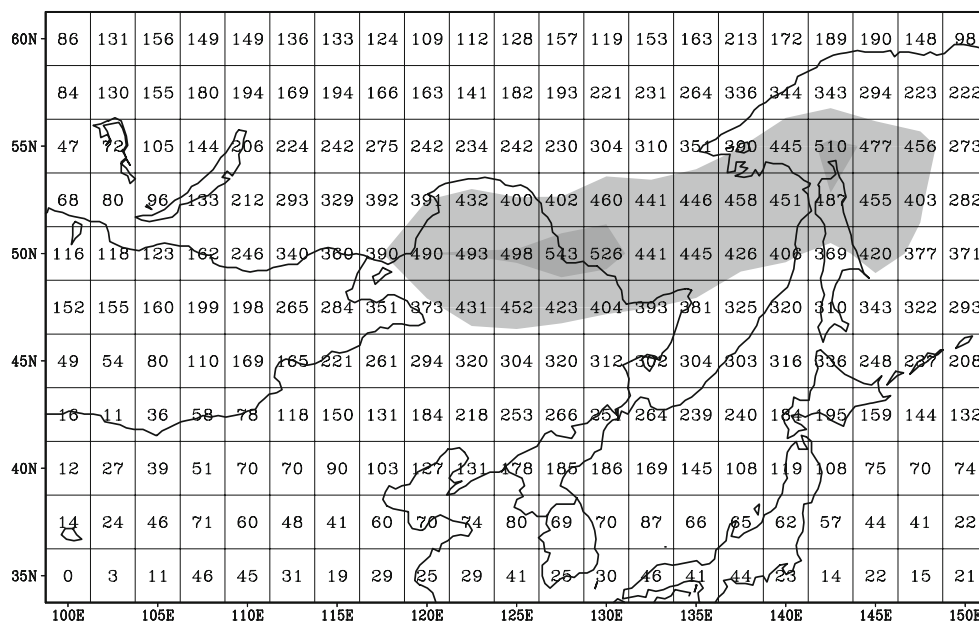


Fig. 3 Spatial distribution of total frequency of COLs in Northeast Asia during the 49-year period. Light and heavy shadings are areas with 392 and 490 units, respectively, namely, 8 and 10 for annual mean

Information Center (NMIC) of CMA. Climatology of daily and seasonal precipitation is defined as mean value for the whole 27-year period. As long as any COL develops in the domain of Northeast Asia, we attribute simultaneous rainfall over this domain to this event, regardless of whether the effect is direct or indirect.

3 Seasonal characteristics of COLs

By the three-step algorithm described in Sect. 2, a multi-decadal database on frequency of COLs can be obtained. Furthermore, more detailed features of any individual COL event, such as duration, size and favorable track, also can be available from this database.

3.1 Spatial distribution of frequency

Figure 3 shows spatial distribution of annual mean frequency of COL in Northeast Asia. It is evident that the most concentrated area of COL has a slightly southwest–northeast oriented band shape with two maximum. The main maximum core (129°E, 50°N), with value larger than 8, locates over northern Northeast China Plain. This dense center overlaps the low-lying area (Fig. 4), which implies that topography has an important role in the development of COL, like COLs in the lee side of the Andes (Fuenzalida et al. 2005). The other slightly weaker maximum center (142.5°E, 54°N), lies over western North Pacific coast. Despite smaller area, its central intensity is roughly



Fig. 4 The locations of the major rivers and mountains in Northeast China

equivalent to the main density center. This result is consistent with that of Porcù et al. (2007), who found that lower sea surface temperature can inhibit convection development and slow down the decay process of COLs in Europe–Atlantic sector, suggesting that the heating difference between Northeast Asia and the North Pacific may influence the evolution of COL.

Spatial distribution of COLs varies with seasons. Figure 5 shows the frequency distributions in spring (MAM, i.e., March–May), summer (JJA, i.e., June–August), autumn (SON, i.e., September–November) and winter (DJF, i.e., December–February). With seasonal march, frequency maximum has an east–west orientation oscillation. In spring and autumn, the frequency center lies around the annual mean climatological location, about

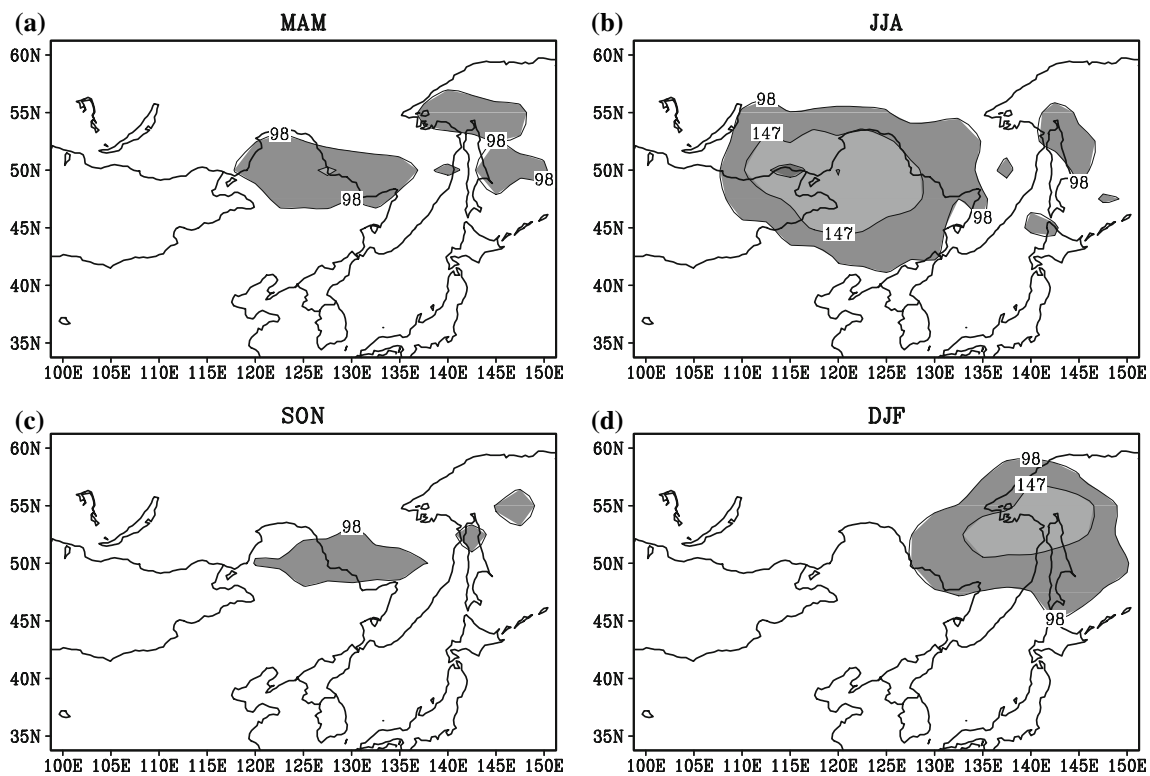


Fig. 5 Spatial distribution of seasonal frequency of COLs in **a** MAM, **b** JJA, **c** SON and **d** DJF. Light and heavy shadings are areas with 98 and 147 units, respectively, namely, 2 and 3 for annual mean

50°N. The maximum moves toward the Eurasian continent during summertime and retreats back to western North Pacific coast in winter, which is similar to the results by Nieto et al. (2005). This may account for the two maxima of Fig. 3. With regard to the summer extension to the continent of COLs in Asia, Nieto et al. (2005) related this zonal oscillation possibly to the strength and position of the upper-level jet streams.

With regard to intensity, the maximum reach its peak in summer with value larger than 3 times/year, followed by winter and spring. In autumn, only 2 times of COLs develop in the maximum center. This is consistent with the spatial distribution of frequency in COL in Fig. 3.

3.2 Temporal variation of frequency

In this subsection, we examine the temporal variation of frequency of COLs in the specified region, i.e., 100°–150°E, 30°–65°N. It should be noted that here, “days” mean the number of total days when COL occurs in each month or year hereafter.

Figure 6 shows the monthly occurrence of COLs in Northeast Asia. It is evident that both number and days for COLs have a seasonal cycle, and summer is the most favorable season for occurrence. Activities of COLs in cold season (October–April) are relatively less frequent,

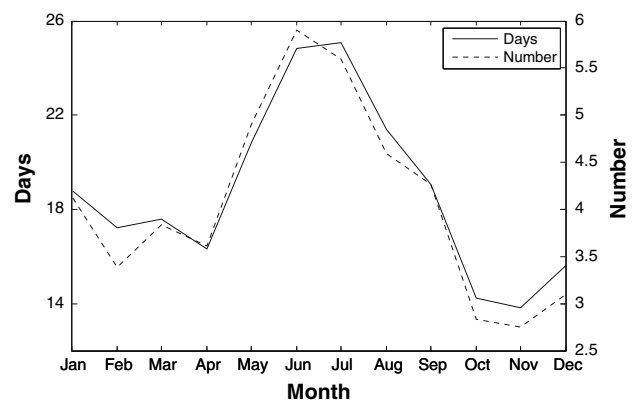


Fig. 6 Monthly distribution of COL for days (solid line) and number (dashed line) based on objective analysis

especially in October and November. On average, COLs can affect weather condition over Northeast Asia for about 24 days in each month of June and July, but less than 15 days in each month of October and November. Monthly variation in days and number are consistent, implying that the duration of COLs does not change much with month.

Frequency of occurrences for COL has a considerable interannual variability (Fig. 7); 59 COLs developed in 1980 while the number in 1964 is only 38. The largest year-to-year variation appears over two consecutive years,

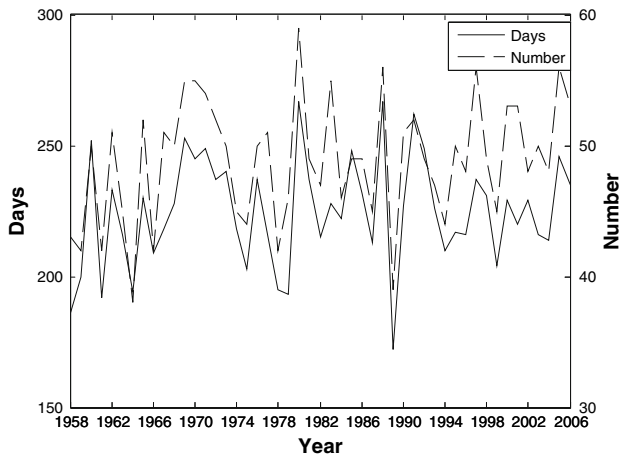


Fig. 7 Yearly variation of COLs for days (*solid line*) and number (*dashed line*)

increasing or decreasing trend during 1958–2006, and the seasonal numbers show a significant increasing tendency for spring but not for other seasons (not shown). Days and number of COL have a good coherence in Fig. 7, with a correlation coefficient of 0.827, suggesting that the duration of COL does not change much year to year.

3.3 Duration and size

Duration of a COL event is defined as the difference between initial time and final time when it can be detected during its lifetime. More than half of detected COLs are with short lifetime (Zhang et al. 2008), and most of short-lived systems are either shallow troughs or secondary minima with complex systems (Trigo et al. 1999). Thus, only COL events lasting no less than 2 days are retained

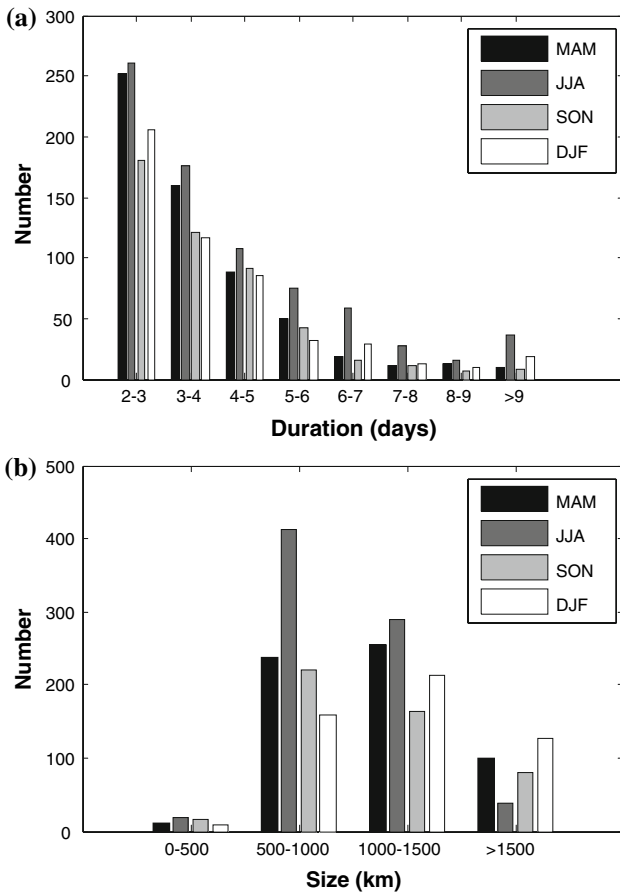


Fig. 8 Duration (a) and size (b) of COLs over Northeast Asia. On the left axis is shown total number of COLs

1988 and 1989, in which there are 267 and 172 days for COLs, respectively. On average, about 49 COLs, which cover 225 days, occur in Northeast Asia in each year. The annual number of COLs does not exhibit a significant

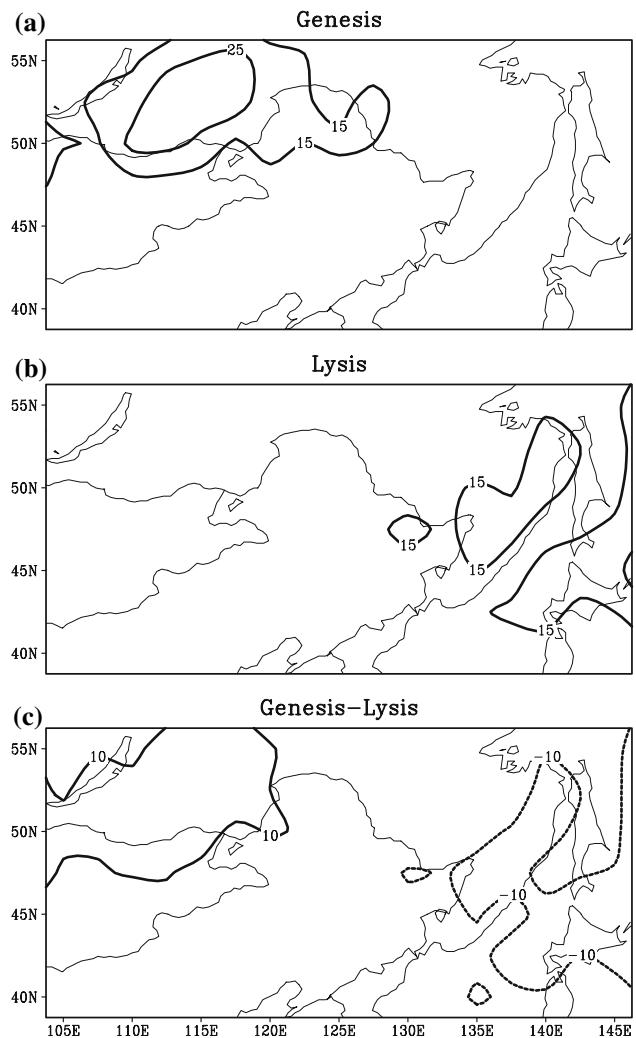


Fig. 9 Genesis (a), lysis (b) and their difference (c) of total frequency of COLs over Northeastern Asia. *Bold contours* are 15 and 25 units for a and b, -10 and 10 units for c

and considered hereafter. From the duration distribution of COL (Fig. 8a), most of COLs last only 2–4 days. Seasonally, 83.0% for MAM, 71.9% for JJA, 82.4% for SON, and 79.8% for DJF last only 2–4 days. Results also show that the number of the events lasting nine or more days is extraordinarily small (1.7, 4.7, 1.7, and 3.7% for MAM, JJA, SON and DJF, respectively). What is more, COL events in summer and winter are likely to be with longer duration than other seasons, which are the seasons with more frequency of occurrences for COL (see Sect. 3.2).

Similar to Nielsen and Dole (1992), size of COL is defined as the distance between the center and the outmost closed contour. For each event, we mark its size by the longest dimension during lifetime. For convenience, events are classified into four categories: 0–500, 500–1,000, 1,000–1,500 and larger than 1,500 km. Figure 8b shows the total number of COLs for each category in the 49 years (1958–2006). Most of COLs lie in the range between 500 and 1,500 km (81.9, 92.6, 80.3, and 73.1% for MAM, JJA, SON, and DJF, respectively). During cold seasons, a greater percentage of COLs tend to have maximum radius larger than 1,500 km than that in summer season (25.1% for DJF and 4.9% for JJA), which may be related to more convective events in summer that suppress farther development of COL (Porcù et al. 2007).

3.4 Genesis and lysis of COLs

Figure 9 depicts genesis, lysis and their difference in spatial distribution of total frequency of COLs during the 49-year period. In this study, the first (last) detected grid point

during the lifetime of any individual COL is deemed as the genesis (lysis) location. To avoid potential errors resulting from boundary effect, we ignore 5° in the zonal boundary and 2.5° in the meridional boundary. Most of COLs form to the east of Lake Baikal, and decay around the western North Pacific coast. Genesis area is more concentrated than lysis region, which may imply that tracks of COLs exhibit a greater variety in the downstream region than the upstream region. Additionally, to some extent, the orientations from center of positive value to center of negative value in the differences between genesis and lysis can describe favorable movement directions of mid-latitude cyclones (Trigo et al. 1999). From the differences distribution (Fig. 9c), therefore, it can be inferred that most COLs tend to move southeastward or eastward.

On seasonal scale, spatial patterns of COL genesis (Fig. 10) and COL lysis (Fig. 11) are similar to pattern of annual mean frequency (Fig. 9). Seasonally, the COL-genesis distribution tends to be in an elongated shape ranging from 115°E to 140°E in DJF, which may attribute to the weaker dense center (142.5°E , 54°N) of total annual spatial distribution of COLs (Fig. 3). In JJA, COL-lysis area distributes more dispersedly and the maximum extends toward continent.

Figure 12 shows seasonal distribution of frequency differences between genesis and lysis. As a whole, difference patterns in each season are similar to the annual mean differences, that is, net source to east of Lake Baikal and net dissipation around the coast of west North Pacific, specially in MAM and SON. The words “net source” (“net dissipation”) here mean that the genesis (lysis) of COLs is dominant over the regions. In DJF, net source area shifts

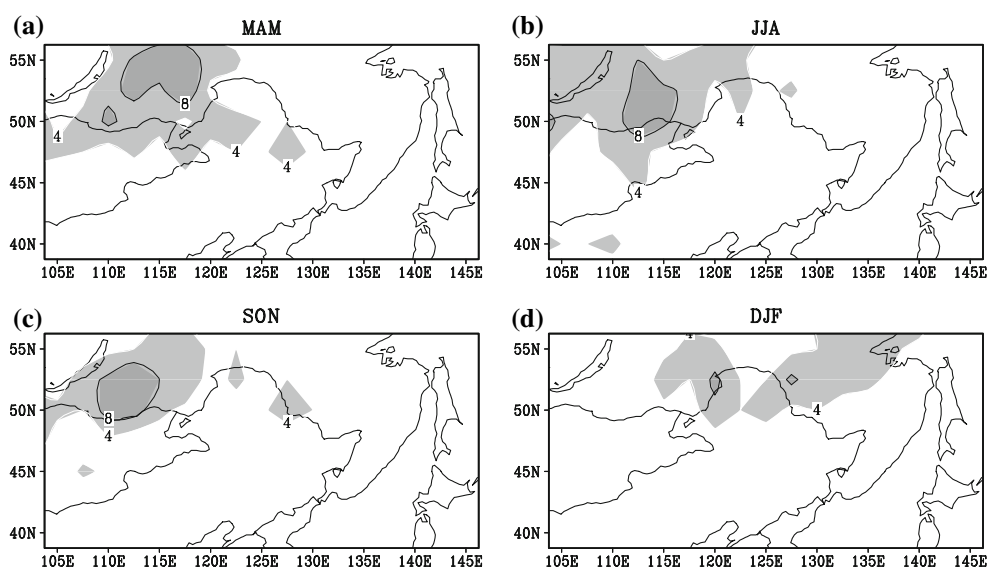


Fig. 10 Seasonal spatial distribution of genesis frequency of COLs in **a** MAM, **b** JJA, **c** SON and **d** DJF. Light and heavy shadings are areas with 4 and 8 units, respectively

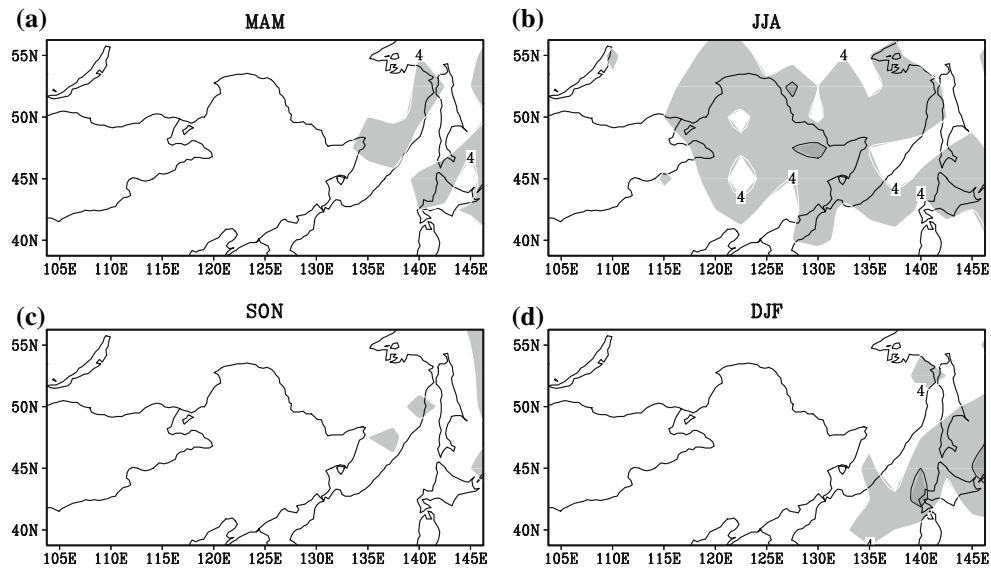


Fig. 11 Same as Fig. 10, but for lysis frequency. Light and heavy shadings are areas with 2 and 4 units, respectively

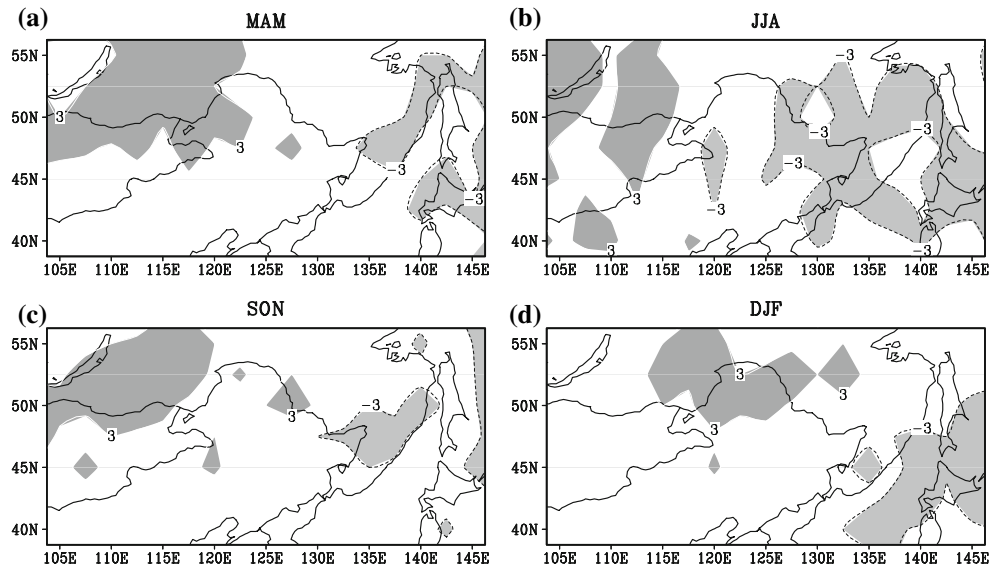


Fig. 12 Same as Fig. 10, but for frequency difference between genesis and lysis. Light and heavy shadings are areas with -3 and 3 units, respectively

eastward about 10° and net dissipation area moves to around northern Sea of Japan, indicating that most COLs may move more southeastward. In JJA, more pronounced minima appear over continent, which suggests more complicated tracks or shorter durations of COLs.

4 Seasonal precipitation patterns associated with COLs

Figure 13a shows spatial distribution of annual precipitation from 1979 to 2005. Climatologically, precipitation decreases along southeast–northwest orientation in Northeast China,

with maxima 1,055 mm in Kuandian (124.47°E , 40.43°N) and minimum 249 mm in Xinbaerhuqi (116.49°E , 48.4°N). This spatial distribution of precipitation is basically determined by summer monsoon circulation (e.g., Zheng et al. 1992; Sun et al. 2007) and by the terrains in Northeast Asia (Wang and Xie 1994), as well as by the COLs (see Fig. 13b). In addition, seasonal difference of precipitation pattern over Northeast Asia is distinct (e.g., Zheng et al. 1992; Lian and An 1998; Jia et al. 2003). Most areas in Northeast China have annual precipitation amounts more than 300 mm in summer (Fig. 14b), while these values are less than 20 mm in winter period (Fig. 14d).

COLs significantly affect disastrous weather in Northeast China. However, most previous research on relationship between COLs and convective events is either limited to case studies (e.g., Chen et al. 1988; Zhao and Sun 2007), or without noticing seasonal differences (Zhang et al. 2008). In this section, by the use of long-term objective dataset of COLs and observed station precipitation data, seasonal precipitation patterns over Northeast China associated with COLs are illustrated.

The percentage of annual precipitation associated with COLs to total annual precipitation is depicted in Fig. 13b. It should be mentioned that in this paper, precipitation “associated with” COLs represents rainfall that happened during COL days, rather than induced directly by COLs. It is evident that, for most of the region, more than a quarter of total annual mean precipitation is associated with COLs. According to statistic analysis by Zheng et al. (1992), COLs are responsible for about 7% of regional rainstorms and 22% of local rainstorms in Jilin Province of Northeast China. As Zhang et al. (2008) adopted a more rigorous threshold value of geopotential height (40 gpm) to detect COLs, it is likely that quite a few shallow and weak COL events may have been filtered out. Therefore, the ratio of precipitation limited to deep and strong COL systems in their study is much higher than our work.

Moreover, over the areas where annual precipitation is less (Fig. 13a), such as the northern and western part of Northeast China, rainfall is more likely to be linked to COL, which is consistent with result of Zhang et al. (2008). In these regions, precipitation associated with COLs accounts for more than 30% of annual total. Thus, it may be indicated that precipitation over northern and western part of Northeast China is relatively more affected by COLs, while the rest may be more related to the southerly flows of East Asian summer monsoon circulation.

The ratios of COL-associated precipitation to total precipitation also have remarkable seasonal differences (Fig. 15). Even though COLs are less active in MAM and SON, the ratios are larger than 30% over most of the region. On the other hand, in JJA, the most favorable season for development of COL, precipitation over Northeast China is least likely to be associated with COLs, with the ratio being lower than 30% over the whole region. This can be explained by that precipitation in summer is more related to East Asian monsoon.

5 Conclusions

In this study, by using 49-year NCEP/NCAR reanalysis data and daily rain-gauge records in Northeast China during 1979–2005, seasonal climatology of COLs and associated precipitation patterns over Northeast China are

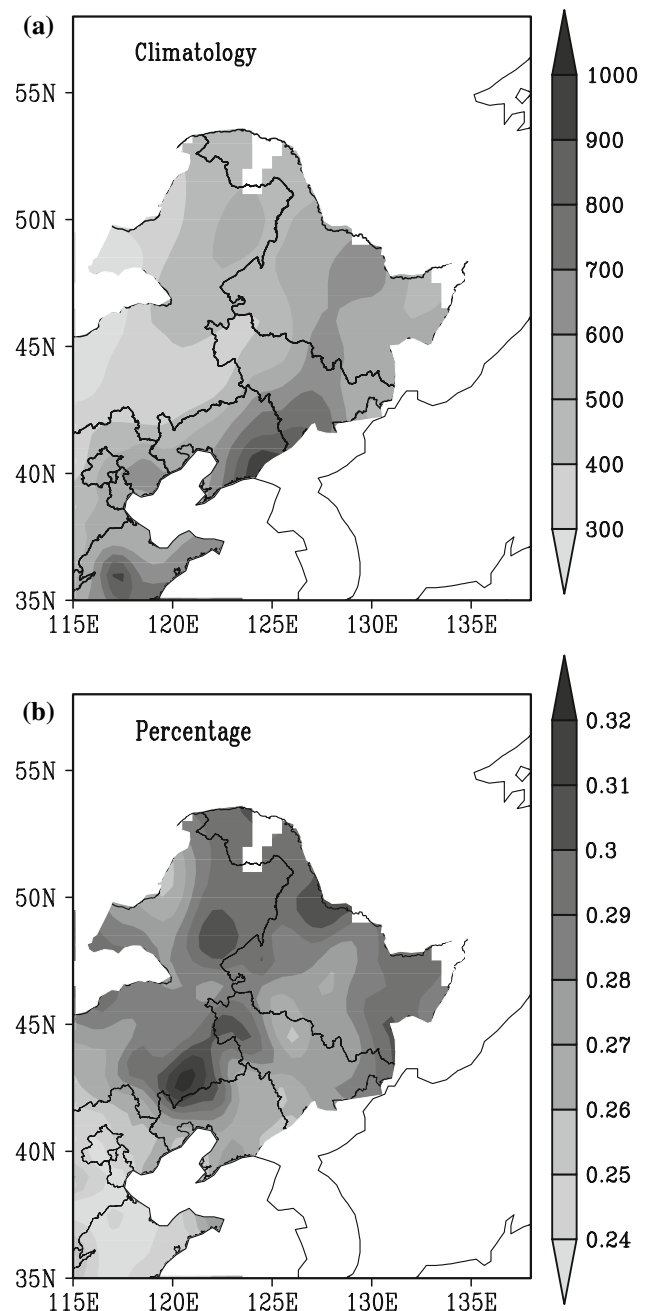


Fig. 13 Spatial distribution of **a** annual precipitation (unit, mm) and **b** percentage of precipitation associated with COLs to total annual precipitation

analyzed. At first, based on a three-step objective method of synoptic concept of COL, a multi-decadal dataset of COL in the Northeast Asia is obtained. Then, using this dataset, the seasonal characteristics of COLs over Northeast Asia, such as frequency, duration, radius, genesis, lysis and favorable tracks are revealed. Finally, seasonal precipitation patterns associated with COLs over Northeast China are briefly discussed. The main conclusions can be summarized as follows:

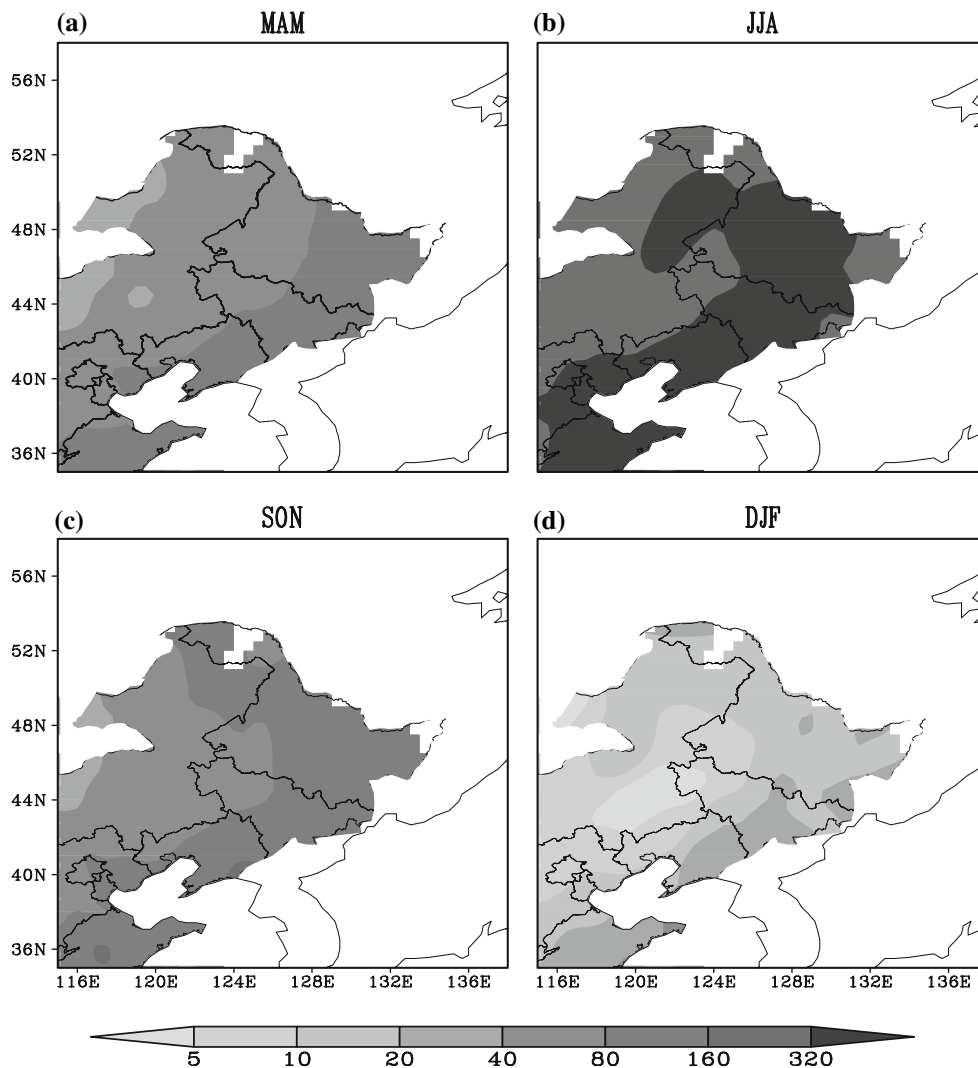


Fig. 14 Spatial distribution of seasonal precipitation in **a** MAM, **b** JJA, **c** SON and **d** DJF

- In general, most COLs have a short lifetime of less than a week, and are apt to have longer duration in summer and winter. Also, most of COLs have a large scale size, ranging between 500 and 1,500 km, and a greater percentage of COLs have a larger size in cold seasons than in warm seasons.
- The frequency of COLs has a seasonal cycle with peak phase in summer and bottom phase in late autumn and early winter. Annual frequency of COLs has a considerable interannual variability with no significant long-term trends.
- The spatial distribution of annual frequency has a main center over northern Northeast China Plain and a secondary center over western North Pacific coast. The density band of frequency has a zonal oscillation with season, namely, extension to continent in summer and approach to coast in winter.
- Most of COLs form to the east of Lake Baikal, and end their lifetime over western North Pacific coast. COLs are apt to move along east or southeast passage, and tracks are relatively more complicated in warm seasons.
- About a quarter of the annual mean precipitation over Northeast China is associated with COL systems. In particular, the ratios of COL-associated precipitation to total precipitation are relatively larger in northern and northwestern parts of this area than other regions. The ratios are the greatest in spring and autumn, and the smallest in summer.

In this study we focus on the statistical results of climatological features of COLs. The physical processes responsible for these features, such as the interaction between COLs and upper-tropospheric westerly jet, and the

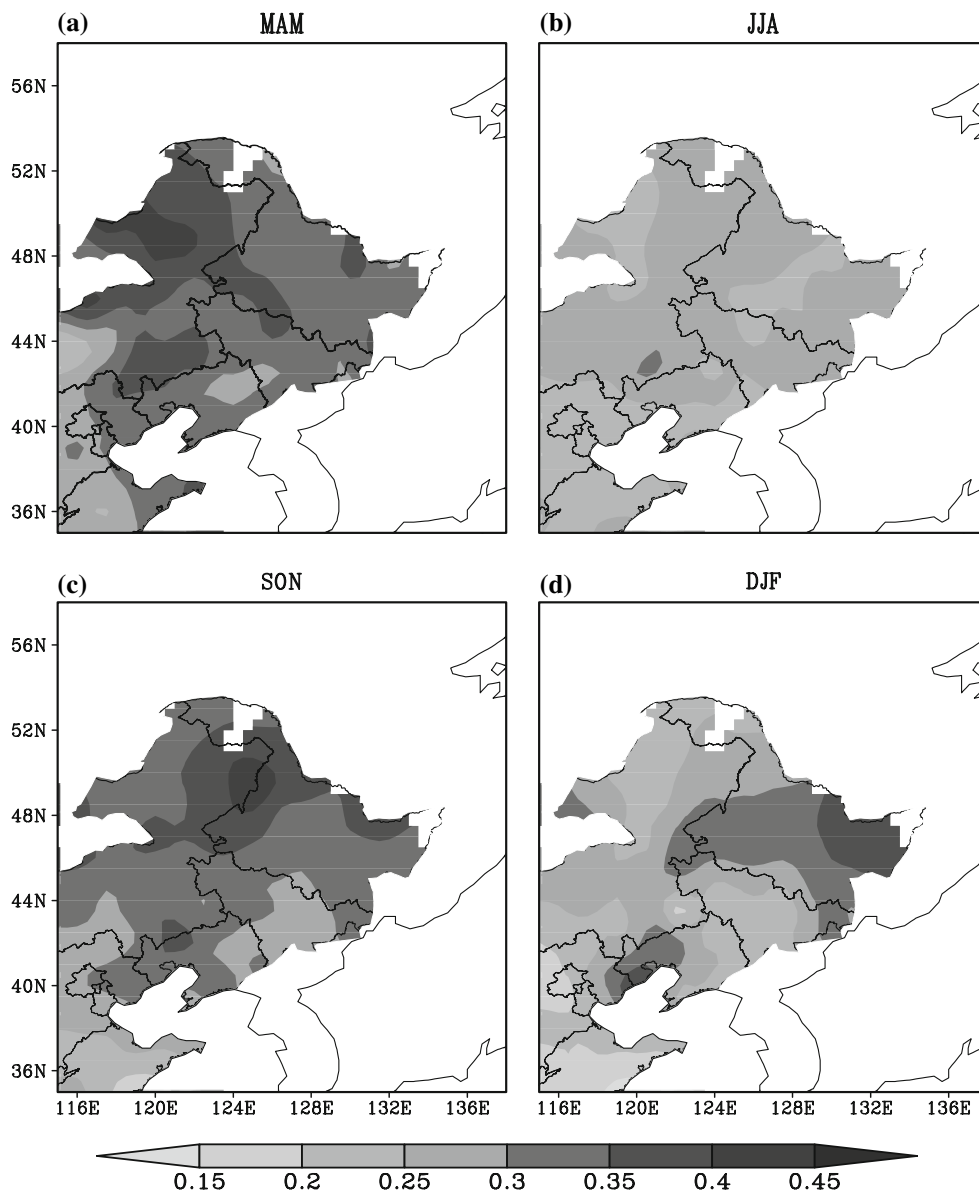


Fig. 15 The percentage of precipitation associated with COLs to total seasonal precipitation

detailed characteristics of COL-related rainfall are not well known and need to be studied further.

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