Interannual Variation of Cold Frontal Activity in Spring in Mongolia

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Abstract

In Mongolia and northern China, most of the dust storms in spring occur in association with a passage of cold front formed at the leading edge of cold air outbreak. In this study, we propose an index to evaluate a cold frontal activity by identifying "cooling days". These are days when there is a strong decrease in daily mean surface air temperature of greater than 5 K, using the European Centre for Medium-Range Weather Forecasts 45-year reanalysis data for 1967 through 2002.

The geographical distribution of seasonal mean cooling day frequencies showed that Mongolia is the most frequent area over Eurasia with the highest frequency of cooling days in spring.

Interannual variations in the area-averaged frequency of cooling days in Mongolia showed that most of the years with less-than-average frequencies in spring occurred in the last 20 years. To determine the main cause(s) for the differences in cooling day frequencies, we conducted a composite study for the 8 years with the highest area-averaged spring cooling day frequencies (active years), and the 8 years with the lowest (inactive years). This study revealed that there were no apparent differences between the active and inactive years with regard to geographical route of cold air, or total number of cooling events. In contrast, the cooling intensity in the inactive years was approximately 20% below that in the active years. These results suggest that recent weakening of cooling intensity over eastern Mongolia has resulted from warming over Siberia.

1. Introduction

Cold fronts are one of the most important weather systems. In East Asia, strong cold frontal systems are frequently formed in association with the cold air outbreaks during cold seasons. Previous studies have shown that the cold air outbreaks are accompanied by dramatic decreases in temperature, increases in pressure, and intense northerly winds (Boyle and Chen 1987; Ding 1994; Zhang et al. 1997).

Unfortunately, as discussed by Zhang et al. (1997) and Compo et al. (1999), an index to define cold air outbreaks is different in each

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study. Most of these definitions have been made by complex combinations of several meteorological variables based on surface observational data. Because of the complicated procedure, and the difficulty of obtaining observational data, most of these pre-defined indices of cold air outbreaks were only used in the studies concerned. Consequently, reaching a consensus about long-term variations in the activity of cold air outbreaks have been hindered.

Another problem with these varying definitions is that it is difficult to adapt them to gridded data, such as future climate predictions based on different scenarios in CO2 emission. As Folland et al. (1999) pointed out, to examine the long-term variations of climate extremes, the key indices should be defined by both observational and simulated data.

Cold fronts also influence the long-range transport of mineral dust in East Asia. Most dust storms are observed in spring, accompanied by the passage of cold fronts in northern China and Mongolia (Sun et al. 2001; Shao and Wang 2003). The suspended dust troubles human society: it obstructs traffic by creating bad visibility, and adversely affects human health.

On the basis of long-term record of surface observational data, several studies have reported that the frequency of dust storms in East Asia is decreasing, particularly over the last 20 years (e.g., Qian et al. 2002; Sun et al. 2003). These studies suggest that the decreasing trend in dust storm frequency is related to recent climate change. However, the observational analyses conducted in these studies were based on visibility at surface meteorological observation sites, and, as discussed by Shao and Wang (2003), such surface weather report data may contain spatial or temporal inhomogeneities arising from different judgements by the observers.

Zhang et al. (2003) examined the interannual variations in dust emission in East Asia using a numerical model. They found that the decreasing trend in dust emission observed in recent decades is primarily controlled by changes in meteorological conditions.

Serreze et al. (2001) studied frontal activity in the Northern Hemisphere by using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data. Despite the coarse horizontal resolution, this study provides a comprehensive descriptions of frontal activity, both in the spatial pattern and seasonal change. Unfortunately, frontal activities in elevated areas (e.g., the Mongolian Plateau) were masked in their study, because their definition of frontal activity was determined by the horizontal temperature gradient at the 850-hPa level. Fundamental information on frontal activity over mountainous areas is still insufficient compared with oceanic storm tracks.

Therefore, definition of cold-frontal activity that can be adopted in elevated areas will provide an important perspective into the typical characteristics of frontal activity in such areas. In particular, frontal activity on the Mongolian Plateau may also be used to evaluate the atmospheric “potential” of dust storm occurrences.

In the present study, we propose a simple index to the passage of cold fronts. To validate our definition, we examine geographical distributions of the passage of cold fronts, and seasonal changes in their frequency in comparison with earlier studies. Interannual fluctuations in cold frontal activity in Mongolia are also analysed.

2. Data and methodology

In this study, the passage of a cold front is identified simply by the differences in daily mean temperature at a selected point: \( \Delta T(t) = T(t) - T(t-1) \), where \( T(t) \) represents the daily mean surface air temperature on the \( t \)-th day. When \( \Delta T(t) \) exceeds the threshold value \( \Delta T_* = -5 \) K, we refer to the \( t \)-th day as a “cooling day”. In general, representative value of temperature cooling associated with a cold frontal passage varies by season and geographical location. However, to detect a cold frontal passage as simple as possible, we use the constant threshold value, which is empirically determined and referred to previous studies (e.g., Joung and Hitchman 1982; Lau and Lau 1984). Since these studies were interested in cold air outbreaks in winter, the threshold value \( \Delta T_* = -5 \) K may be slightly severe condition to detect a traveling cold frontal system throughout a year. Consequently, we consider a frequency of cooling day as an indicator of the activity of strong cold frontal systems, and use that to determine primary frontal zones over Eurasia in the following section.
We used the 6-hourly 2-m temperature (hereafter surface temperature) from the European Centre for Medium-Range Weather Forecasts (ECMWF) 45-year reanalysis (ERA-40) data. The data have a horizontal resolution of $1.125^\circ \times 1.125^\circ$. Daily mean temperatures were obtained by averaging four times daily values. The analysis in this study is limited to the period from 1967 through 2002. As pointed out by Simmons et al. (2004), the surface temperature data includes a gap between 1966 and 1967, that is mainly caused by the lack of surface observations, particularly in East and South Asia (see Fig. 2 of Simmons et al. 2004).

The world surface data, which is based on SYNOP bulletins submitted by members of the World Meteorological Organization (WMO) through Global Telecommunication System (GTS), are obtained from the Japan Meteorological Agency (JMA). The 6-hourly report of present weather events is used to obtain the date of dust outbreaks.

As an example of cooling days, Fig. 1 presents daily mean surface temperatures from 1 October 2001 to 31 May 2002 at 43.875°N, 112.5°E, where severe dust storms occur most frequently in East Asia (Shao and Wang 2003). The gray bars represent days of dust outbreaks, observed at Erenhot, China (43.65°N, 112.00°E, 966 m). The day of dust outbreaks were identified by the code number of present weather (ww = 07, 08, 09, 30–35, and 98).

![Figure 1](image.png)

Fig. 1. Daily mean surface air temperatures (thin solid line) during October 2001 through May 2002 at 43.875°N, 112.5°E. Dashed line shows average daily surface air temperatures for 1971–2000. Shaded circles with thick lines represent identified cooling days. "Cooling day" is defined in section 2. Light bars represent the day of dust outbreaks (A–H), observed at Erenhot, China (43.65°N, 112.00°E, 966 m). The day of dust outbreaks were identified by the code number of present weather (ww = 07, 08, 09, 30–35, and 98).
The largest cooling for this period was observed on 6 April 2002. Daily mean surface temperature abruptly decreased from 5 April (284.1 K) to 6 April (268.1 K). During the cooling period, intensive dust storms were extensively observed over arid, and semi-arid areas in Mongolia and China (In and Park 2003; Chung et al. 2003).

Figure 2 shows the daily mean surface temperatures (contour) and daily temperature changes in a day (shade) during 4–8 April 2002. Sea level pressure (SLP) and 10-m wind are also shown in Fig. 3. On 4 April (Figs. 2a and 3a), two days before the largest cooling day, strong cooling area ($\Delta T < -5$ K; dark shaded) extended northeastward from north of the Tianshan Mountains, through the Altai–Sayan Mountains, into the northwest of Lake Baikal. This cooling area located in the eastern part of a Siberian high where the northwesterly wind is dominant (Fig. 3a).

During the next two days the strong cooling area moved southeastward from the Altai–Sayan Mountains to eastern Mongolia (Figs. 2b and 2c). On 6 April, the area of large temperature cooling ($\Delta T_{2m} < -5$ K) and prevailing northwesterly winds ($|V_{10m}| > 10$ ms$^{-1}$) extensively covered eastern Mongolia and northern China (Figs. 2c and 3c). In the southeastern part of the strong cooling area, isotherms were highly crowded (Fig. 2c). This strong temperature gradient represents the cold frontal zone, formed in the leading edge of the cold air outbreak.

After the largest cooling day, the primary center of the cooling area shifted southward to the east of the Tibetan Plateau (Fig. 2d). On 8 April, the cooling area was still identified, and advanced steadily southward along the eastern boundary of the Tibetan Plateau (Fig. 2e).

We also examined for other cooling days. Spatial patterns of cooling areas and their temporal evolutions were similar to this event, that is, strong cooling area with strong wind behind a cold front migrated southeastward from the West Siberian Plain to East Asia (not shown).

3. Validation of the cooling days

Figure 4 shows the horizontal distribution of seasonal mean frequencies of cooling days for 1967 through 2002 over Eurasia. The cooling day frequency ($f_{cd}$) in each grid cell is expressed as the ratio of total cooling days to the total number of days in each season. For convenience, we define that region whose $f_{cd}$ exceeds 0.03 day$^{-1}$, which corresponds to approximately one cooling day per month.

In winter (December–February), the cooling region broadly covers the Arctic Ocean and northern Eurasia to the east of 30°E (Fig. 4a). The area of highest $f_{cd}$ (0.18 day$^{-1}$ at 67.5°N, 77.625°E) is located north of the West Siberian Plain. Although a well-defined meridional gradient of $f_{cd}$ is located along 45°N to the west of 80°E, the distinct gradient zone shifts northward from 80°E to 120°E. This meridional displacement reflects the barrier effect of high mountains (Tianshan, Altai, Sayan, Hangayn, Yablnovy, Stanovoi, and Verkhoyansk) on the transport of cold air.

Other peaks in cooling day frequency are observed around the Svalbard Islands, Mongolia, and the seaboard along the Sea of Japan. The Svalbard Islands locate the marginal zone of Arctic sea ice in winter; there is a strong temperature gradient, where horizontal and vertical mixing are frequently observed in association with the intrusion of synoptic disturbances from the north Atlantic (Enomoto et al. 1993).

In spring (March–May), $f_{cd}$ is generally smaller than that in winter, except in eastern Mongolia (Fig. 4b). Two centers of high $f_{cd}$ are evident, one over the West Siberian Plain, one over eastern Mongolia and Inner Mongolia in China. The maximum frequency over eastern Mongolia (0.12 day$^{-1}$ at 42.75°N, 112.5°E) is about four cooling days per month. The area of highest $f_{cd}$ corresponds to the area of most frequent dust storm events (Sun et al. 2001; Shao and Wang 2003; Kurosaki and Mikami 2003), and the highest activity of cyclogenesis (Chen et al. 1991). From Fig. 4b it can be seen that the cooling region extends to low latitudes to the east of the Tibetan Plateau. The southward extension of the cooling region represents the clockwise (southward) migration of cold fronts along the eastern boundary of the Plateau (Figs. 2d, e). As shown by Sun et al. (2000), cold fronts accompanied by dust storms are frequently observed in this area.

Summer (June–August) has the lowest frequency of cooling days in Eurasia (Fig. 4c). Areas of high $f_{cd}$ are observed in two latitudi-
Fig. 2. Daily mean surface air temperatures (contour) and daily mean temperature changes in a day (shaded) for 4–8 April 2002. Contour interval is 5.0 K (contour) and 2.5 K (shaded).
Fig. 3. Sea level pressure (SLP; contour interval 4 hPa) and 10-m wind (vector). Wind speed smaller than 3 ms\(^{-1}\) is omitted at 0600 UTC 4–8 April 2002. Light (heavy) shaded areas represent the region where the wind speed exceed 6 ms\(^{-1}\) (10 ms\(^{-1}\)).
nal belts, one in the northern part of Eurasia along the coast of the Arctic Ocean, and the other inland along 45°–50°N. Locations of these two belts of high cooling day frequency correspond to the Arctic and polar frontal zones in Eurasia, respectively (Serreze et al. 2001; Fukutomi et al. 2004).

In autumn (September–November), a large area of high \( f_{cd} \) covers northeastern Asia north of 40°N (Fig. 4d). As with spring, there are two frequency peaks, one in eastern Mongolia and one in Siberia. Although the location of the area of highest \( f_{cd} \) in Mongolia remains almost stationary throughout the season, the area of highest \( f_{cd} \) in Siberia is displaced poleward from 45°–55°N in September, to 55°–65°N in November (not shown). Possible reasons of this displacement are the seasonal transition of atmospheric circulation pattern and the extent of snow cover.

As shown in Fig. 4, the region of eastern Mongolia and Inner Mongolia in China has a high \( f_{cd} \) throughout the year. This area also corresponds to a region of major dust storm occurrence. For these reasons, the analysis in the following section focuses on the area between 39.375°–50.625°N, and 102.375°–120.375°E (enclosed by the dashed rectangle in Fig. 4d). The area-averaged frequency of cooling days (\( \langle f_{cd} \rangle \)) is calculated from the sum of cooling
days divided by the product of total number of days and total number of grid cells within the analysis area. It should be noted that the calculated values represent the activity of strong cold frontal system, but are not always proportional to a total number of passages of cold front. Since the threshold set to constant value, strong (weak) cold fronts provide a large (small) number of grid cells within the analysis area. Persistence of cooling day also affect that value. The relationships between \( \frac{f_{cd}}{C} \) and statistics of cooling events will be discussed in section 4.

The seasonal evolution of monthly mean \( f_{cd} \) is shown in Fig. 5. There are two frequency maxima in late autumn (October to November), and late spring (April to May). The double peaks in the annual cycle are consistent with the frequency of cold air outbreaks in East Asia (Zhang et al. 1997).

To validate the results shown in Fig. 4, we used surface observational data from the Global Surface Summary of Day data, version 6, for January 1994 through August 2002, from the National Climatic Data Center/National Oceanic and Atmospheric Administration (NCDC/NOAA). Although the spatial distribution of these surface stations is not homogeneous, the spatial patterns and the seasonal evolutions in the frequency of cooling days are in good agreement with the results shown in Fig. 4 (not shown).

The large \( f_{cd} \) area for springtime in East Asia extends southeastward from south of Lake Baikal to northwest of Beijing (Fig. 4b). This spatial pattern of \( f_{cd} \) maximum is similar to one of the primary routes of cold air outbreaks accompanying dust storm events (Sun et al. 2001), and to a major track of surface anticyclones originated from western and central Siberia (Ding and Krishnamurti 1987; Zhang et al. 1997).

Overall, the frequency of cooling days can be considered to represent the activity of traveling cold frontal systems, or cold air outbreaks, throughout all seasons over Eurasia. In particular, the frequency of cooling days can also express a cold frontal activity over the Mongolian Plateau, a region which is masked in the results of Serreze et al. (2001).

4. Interannual variations in the frequency of cooling days in Mongolia

Recently, several studies have shown that dust storms have become less frequent in China and Mongolia, particularly after the 1980s (Qian et al. 2002; Sun et al. 2003; Zhang et al. 2003). In this section, we examine the interannual variations in the frequency of cooling days in Mongolia.

The seasonal mean \( f_{cd} \) in Mongolia for 1967 through 2002 is shown in Fig. 6. Large circles and squares represent the 8 highest and 8 lowest values in this period, respectively. Note that for the spring observations, the years with the highest \( f_{cd} \) values tended to be in the first half of the 1967 to 2002 period, whereas the years with lowest \( f_{cd} \) values tended to be in the second half (Fig. 6c). This is consistent with the trend toward decreasing frequency of strong cold air outbreaks in Mongolia and northern China (Zhai et al. 1999), and the weakening of cyclone activity over Mongolia (Qian et al. 2002). The interannual variation is not as obvious in autumn and winter as it is in spring.

As mentioned in section 3, \( f_{cd} \) is determined by the sum of the cooling days for all grid cells in the analysis area divided by the product of the total number of days and grids. Therefore, any variation in \( f_{cd} \) is expected to be caused by one or more of the following factors: (1) geographical differences in cold air pathways, (2) differences in cooling intensity during cooling period, and (3) temporal changes in passage of the cold air.
In order to identify the dominant factor(s) in the differences of $\frac{1}{2}f_{cd}/C138$, we examined composites of the 8 years with highest $\frac{1}{2}f_{cd}/C138$ values for spring of 1967 through 2002 (active years), and the 8 years with lowest values (inactive years). The years used in these composites are marked with circles and squares in Fig. 6c.

The geographical distributions of $f_{cd}$ based on these composites are shown in Fig. 7. Although the difference in frequency of cooling days is remarkable, it seems that there is no obvious spatial difference between the two composites with regard to the geographical location of the frequency maxima. This result suggests that the difference in $f_{cd}$ between the active and inactive years in Mongolia does not depend on the spatial changes in cold frontal pathways.

We then discuss the cooling intensity and the frequency of cold frontal passages over Mongolia. Recall that the identified cooling days are determined by using constant threshold value ($\Delta T_r = -5$ K). Based on this definition, it could fail to detect a weak cold frontal system which has a smaller temperature gradient. In order to assess the changes in frequency of cold frontal passages, it is necessary to count the total number of cold frontal passages, including weak ones, over Mongolia. As shown in Fig. 2, the propagation of cold fronts provides region-wide strong cooling behind the front. Therefore, a period for a cold frontal passage (cooling period hereafter) is simply determined by a negative value in the area-averaged daily-mean temperature change ($[\Delta T(t)] = [T(t)] - [T(t-1)]$). A single cooling event is identified by the successive cooling period ($[\Delta T] < 0$). The total cooling period in each season is obtained from the sum of the number of cooling periods during the season. The key date of the cooling event (Day 0) is defined by the day of the maximum temperature cooling during a cooling period. To evaluate the intensity of a cooling event, we examined two indices obtained from area-averaged temperature changes. One is the total temperature change during a cooling period ($[\Delta T_{total}]$), and the other is the temperature change at Day 0 ($[\Delta T]$).

On the basis of these definitions, cooling events occurred an average of about 19 times in spring, which corresponds to one cooling event every 4 to 5 days. The cooling event defined above include most of the identified cooling days in each grid cell within the analysis area. Indeed, the cooling period defined by $|\Delta T| < 0$ include 98% of the total number of cooling days, which is identified by daily mean temperature differences at each grid.

Table 1 shows the results of these statistics for the 8 year composites of active and inactive years. As expected, the mean $|f_{cd}|$ difference between the two composites is quite large,
with a ratio of the difference to the climatology reaching about 40%. The differences in \( \Delta T_{\text{total}} \) and \( \Delta T_0 \) are approximately 20%. In contrast, the differences in the mean number of cooling events and the mean cooling period are quite small (smaller than 4% to the climatology). Figure 8 shows the occurrence frequency of cooling intensity at Day 0 \( (\Delta T_0) \) during spring. The histogram represents long-term mean for the period 1967–2002. Solid and dashed line depict the active and inactive composites, respectively. Comparing between the active and inactive years, strong cooling events in the inactive years are less frequent than in the active years. For example, while the frequency of cooling intensity below \(-5.0\) K for the active years show 21% in total cooling events, the frequency for the inactive years are only observed 10% in total. In contrast, the frequency of weak cooling events, particularly in the range of temperature decreases from \(-2\) to \(0\) K, show opposite sense between the active and inactive years. These results indicate that the changes of cool-

<table>
<thead>
<tr>
<th>8-year composites in spring</th>
<th>( [f_{\text{tot}}] ) (day(^{-1}))</th>
<th>Number of cooling events</th>
<th>Period (day)</th>
<th>( \Delta T_{\text{total}} ) (K)</th>
<th>( \Delta T_0 ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>0.105</td>
<td>19.5</td>
<td>38.6</td>
<td>(-4.53)</td>
<td>(-3.13)</td>
</tr>
<tr>
<td>Inactive</td>
<td>0.069</td>
<td>18.6</td>
<td>37.0</td>
<td>(-3.65)</td>
<td>(-2.49)</td>
</tr>
<tr>
<td>Climatology</td>
<td>0.088</td>
<td>19.4</td>
<td>38.4</td>
<td>(-4.04)</td>
<td>(-2.76)</td>
</tr>
</tbody>
</table>

Fig. 7. Spatial distributions of springtime cooling day frequencies for 8-year composites of (a) active years (marked with circles in Fig. 6c) and (b) inactive years (marked with squares in Fig. 6c).

Table 1. Seasonal mean statistics for cooling activity in the 8-year composites of active and inactive years over Mongolia in spring.

Fig. 8. Frequency of an area-averaged cooling intensity at Day 0 \( (\Delta T_0) \). (a) Active years (solid line), (b) inactive years (dashed line), and (c) climatology for the period 1967–2002 (histogram).
ing intensity is a major cause of the differences in $f_{cd}$.

Furthermore, the mean difference of $[\Delta T_0]$, between the composites of the active and inactive years (0.64 K), amounts to 70% of the mean difference in $[\Delta T_{total}]$ (0.88 K). Since $[\Delta T_0]$ is determined by the maximum temperature drop in each cooling period, $[\Delta T_0]$ corresponds to the horizontal temperature gradient across the cold front. Therefore, the springtime weakening of $[f_{cd}]$ in recent years is primarily caused by the weakening of the horizontal temperature gradient across the cold front.

5. Discussion and conclusions

In this study, we have proposed a simple index that uses daily mean surface air temperatures to determine the passage of a cold front. Cold frontal passages (“cooling days”) are identified by large falls in the surface temperature, as determined from the ERA-40 data for 1967 through 2002.

The spatial patterns, and seasonal change of cooling day frequency, show that this index is suitable for detecting the passage of cold fronts over continental areas, particularly over elevated areas such as the Mongolian Plateau.

Furthermore, this index can be easily applied to other gridded data sets, to detect the passage of cold fronts or cold air outbreaks. For example, it is a convenient way to assess the ability of numerical models to reproduce the variability of temperature in daily-scale.

As shown in Fig. 6, inactive years of the cooling days in spring in Mongolia are more frequently observed after the mid-1980s. In contrast, difference of temporal occurrences of the active and inactive years between the first half and the second half is not so apparent in autumn and winter as in spring. One of the possible explanations for such seasonal dependence in Mongolia is the effect of snow cover anomalies in recent years. As noted by Groisman et al. (1994), radiative balance in the atmospheric column is largely influenced by the presence or absence of snow cover, particularly in the spring season. According to Groisman et al. (1994), snow cover extent in Eurasia showed a significant decreasing trend for the period 1972–1992. Bamzai (2003) calculated a day of snowmelt, using satellite-derived snow cover during 1972–2000. Their results showed that the areas of earlier snow disappearance, extensively covered over the east 90°E in 48°–60°N. As shown in Fig. 4b, such earlier snowmelt areas are superimposed on the area of large frequency of cooling days. Therefore, it seems that the recent weakening of cold frontal activity may be caused by an increased heating of the cold air on the way to the Mongolian Plateau from Siberia. To verify this hypothesis, it is necessary to conduct a quantitative analysis (e.g., heat budget analysis) during a cold surge period in a future research.

Analysis of years with the highest $[f_{cd}]$ values (active years) and lowest $[f_{cd}]$ (inactive years) showed that the springtime $[f_{cd}]$ in inactive years was 40% below that in active years. The geographical route of traveling cold frontal systems (the relative maximum in $f_{cd}$), and the total number of cooling events were not substantially different (Fig. 7 and Table 1). In contrast, there was a large difference in the intensity of cooling events between the two composites. Average cooling intensity at Day 0 ($[\Delta T_0]$), and over each cooling event ($[\Delta T_{total}]$) in inactive years, were 20% below that in active years (Table 1).

The major axis of the frequency maximum in springtime cooling day, as indicated in Figs. 4b and 7, is quite similar to the spatial pattern of the warming trend in spring (e.g., Folland et al. 2001). In addition, previous studies showed that the decrease in daily temperature ranges were observed over the Former Soviet Union and China in winter and spring (Karl et al. 1993; Karl et al. 1995). As shown in Zhang et al. (1997), cold air outbreaks in Eurasia originate in western and central Siberia. Our results suggest that the recent weakening of cooling intensity in Mongolia is an indication of the changes in day-to-day weather that is caused by warming over Siberia.

While the implication above mentioned may be valuable to evaluate an impact on day-to-day weather changes caused by global warming, further analyses should be needed before considering that. The conclusion that the reduction of cooling intensity is based on analyses of composites of seasonal means. Since spring is a transition season from winter to summer, meteorological conditions vary as the season evolves (e.g., snow cover extent, planetary-scale circulation pattern). Furthermore, not all cool-
ing events are weakened in recent years. As shown in Fig. 1, a strong cooling event was observed on 6 April 2002, the cooling intensity was equivalent to the fifth highest for 1967 through 2002 spring.

In order to understand the cause of the weakening of intensity across cold fronts, much further research is required, not only on the physical processes of frontogenesis (frontolysis) in several case studies, but also on the seasonal change of frontal activity on a monthly, or higher temporal resolution.

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