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Spatio-Temporal Characteristics of Winter Cold Events in China from 1960 to 2020

Haifeng Chen[1,2], Xiaojuan Sun[1*], Shu Zhou[3], Junjun Wang[2], Lin Zhou[2]

[1]Key Laboratory of Meteorological Disaster, Ministry of Education/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China
[2]Guiyang Meteorological Bureau, Guiyang, China
[3]Bijie Meteorological Bureau, Bijie, China
Email: *sxjzy709@nuist.edu.cn

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Abstract

Under the background of global warming, extreme cold events occur frequently. It is important to enhance the understanding of cold air patterns for forecasting cold air and reducing cold air-induced meteorological disasters. The study used the daily minimum temperatures from the National Climate Centre to classify the cold events affecting China into five different grades and the characteristics of different intensity cold events in China during the winter from 1960 to 2020 were analyzed. The results showed that there is little difference in the distribution of the frequency of general cold events from north to south, with duration longer in the north than in the south and an increase in frequency in the north in the last 60 years. The frequency of strong cold events is more in the north of China than in the south of China, and the duration is longer in the south than in the north China, with the frequency decreasing in most parts of the country. In addition to latitude, cold events frequency is closely linked to topography, with basins surrounded by high mountains being difficult to be affected by cold events, especially extreme cold events. In terms of month distribution, December was subject to the highest frequency of cold events and the longest duration of a single cold events process.

Keywords

Cold Events, Spatio-Temporal Characteristics, Winter, China

1. Introduction

Cold event is a weather process in which cold air encroaches southward from

high latitudes. The process of cold air moving southward causes widespread cooling weather, sometimes accompanied by high winds and rain and snow, and the strong cooling weather often also triggers a variety of serious meteorological disasters, causing serious impacts on various aspects of agriculture, transportation, telecommunications and electricity and people's lives, resulting in huge economic losses, and is the biggest disaster in the winter half of the year. It is one of the most disastrous weather events in winter.

For example, from 25 to 30 April 1983, more than 61 million mu of farmland was affected by a nationwide cold wave, involving 22 provinces (municipalities directly under the Central Government and autonomous regions) (Liu, 1990); In 2008, a rare rain and snow storm occurred in a wide area of China, affecting 20 provinces (municipalities directly under the Central Government and autonomous regions), affecting almost all sectors and aspects of people's lives (Wang et al., 2008).

Therefore, cold waves and their changing patterns are an important research direction in the meteorological community. There have been many studies on cold air affecting China, and the cold air affecting China mainly comes from high latitudes such as the Arctic Ocean, Siberia and Mongolia (Tao, 1959; Zhao, 1978; Sun et al., 2017; Tang & Zeng, 2017), entering China from different paths, and the first to affect the northern regions of China, with the cold air gradually densifying and weakening in the process of moving south. Thus, overall, the frequency of cold wave in China decreases from north to south.

Wang Zunya and Ding Yihui (2006) pointed out that the average number of cold waves occurring in the area north of the Yellow River in China is more than four times a year, with two large value zones located in central Inner Mongolia and northern Xinjiang, where the frequency of cold waves is eight times a year, and the lowest in the Qinghai-Tibet Plateau and Tibet. Qian and Zhang (2007) also pointed out that in addition to the high-frequency cooling events concentrated north of 35˚N, a band of high-frequency cooling events exists south of the Yangtze River; in eastern China (east of 105˚E), the low-frequency area for cooling events greater than 10˚C is between the Yangtze River and 35˚N.

Wei Fengying (2008) pointed out that after the warming, the frequency of nationwide cold waves decreased significantly in winter and spring, among which the frequency of cold waves in Inner Mongolia, North China and Jianghuai decreased significantly, and the intensity of cold waves in parts of North China and Xinjiang weakened significantly, which is basically consistent with Qian Weihong and Zhang Weiwei's (2007) findings that the trend of decreasing cold wave events was mainly concentrated in Xinjiang, North China, Northeast China and East China. Wu Hongyu and Du Yaodong (2010) noted a decreasing trend in the frequency of cold wave events in southern China in the last 48 years, with a decrease rate of 0.21 events/10 a. Similar characteristics of change exist in the middle and lower reaches of the Yangtze River (Yao et al., 2011), Yunnan (Hai, 2011), and the Hexi Corridor (Yang et al., 2016). However, there is no significant

decrease in the frequency of cold waves in the Sichuan basin in the context of global warming (Zhou et al., 2010).

Global warming has become a fact in the last hundred years (Zhai et al., 2017; WMO, 2019), and China is also in the process of global warming, but extreme cold events occur frequently in this context (Petre et al., 2012; Zhang et al., 2022), so cold events in winter deserve our attention, and the existing studies on Chinese Most of the existing studies on cold events in China have been conducted on strong cold events such as cold waves, or really on a certain region, lacking a systematic analysis of the characteristics of different levels of cold events. In this paper, we will analyze the spatial and temporal characteristics of different levels of cold events affecting China in winter, using daily minimum surface air temperature data from 1960 to 2020.

2. Materials and Methods

2.1. Data

This paper uses the dataset of daily values of basic meteorological elements (V3.0) from national-level ground-based meteorological stations in China provided by the National Climate Centre of China, spanning the period from December 1960 to February 2021, for a total of 61 winters. To ensure the continuity and completeness of the data, stations with missing measurements during the study period were eliminated, and high mountain stations with an altitude difference of 1500 m or more from the nearest station in the vicinity were removed, and 1794 available stations were selected (**Figure 1**).

2.2. Definition of a Cold Event

This paper classifies single-station cold air into five classes: General cold air (GCA), Strong cold air (SCA), Cold wave (CW), Strong cold wave (SCW), Extreme cold wave (ECA) according to the latest cold air class standard (GB/T20484-2017) and cold wave class standard (GB/T21987-2017) released by

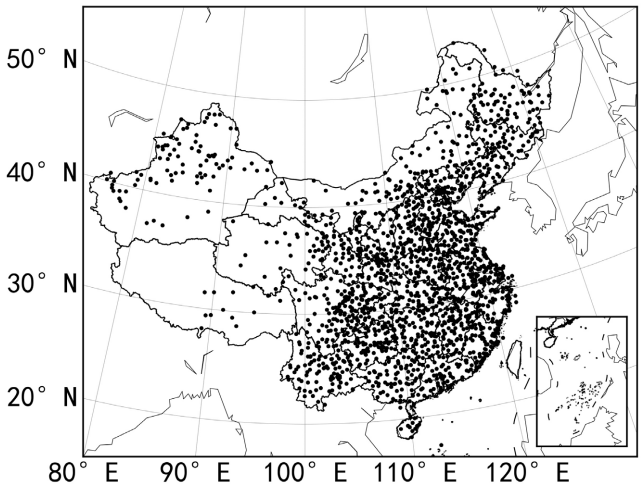

Figure 1. Location of the Study area and the observation station in China.

the Chinese National Standardisation Administration Committee in 2017, which are shown in Table 1.

Daily minimum temperature: the lowest value of temperature between 14:00 of the previous day and 14:00 of the current day as observed.

Decrease temperature range in 24 hours (Dt24): the difference between the daily minimum temperature within 24 hours of 14:00 on a particular day and the daily minimum temperature on that day.

Decrease temperature range in 48 hours (Dt48): the difference between the daily minimum temperature within 48 hours of 14:00 on a given day and the daily minimum temperature on that day.

Decrease temperature range in 72 hours (Dt72): the difference between the daily minimum temperature for 72 hours after 14:00 on a particular day and the daily minimum temperature for that day.

Referring to Wang Zunya et al. (2008), using 32˚N as the dividing line between the north and the south, a regional severe cold event is defined as when the number of stations meeting the single-station cold wave criterion is more than 15% of the total number of stations in the region, and the number of stations meeting the single-station stronger cold air criterion is more than 30% of the total number of stations in the region. A China severe cold event (CCW) is defined when both the southern and northern regions meet the criteria for a regional severe cold event. In addition to the CCW, when the southern region meets the criteria for a regional severe cold event, it is defined as a southern-type severe cold event (SCW), otherwise it is defined as a northern-type severe cold event (NCW).

In this paper, the number of cold events occurring between December of that year to February of the following year is defined as the frequency of cold events in a complete statistical year, e.g. the number of cold events occurring between December 1960 and February 1961 as the frequency of cold events in winter 1960.

3. Result and Discussions

3.1. The Frequency of Cold Events in Winter

3.1.1 The Frequency of Total Cold Events in Winter

In this paper, we calculated the spatial distribution characteristics of the average

Table 1. Cold event rating criteria.

Grade of cold air	Division of grade
General cold air	(6 ≤ Dt48 < 8) or (Dt48 ≥ 8 but Tmin>8)
Strong cold air	Dt48 ≥ 8 and Tmin < 8
Cold wave	(Dt24 ≥ 8 or Dt48 ≥ 10 or Dt72 ≥ 12) and Tmin < 4
Strong cold wave	(Dt24 ≥ 10 or Dt48 ≥ 12 or Dt72 ≥ 14) and Tmin < 2
Extreme cold wave	(Dt24 ≥ 12 or Dt48 ≥ 14 or Dt72 ≥ 16) and Tmin < 0

frequency of different levels of cold events in winter from 1960 to 2020 (Figure 2). From the perspective of the frequency of cold air activity of different intensities, the annual average frequency of General cold air is more evenly distributed across the country, except for the Sichuan basin and southern Yunnan, where the frequency is less than 1 time/year, the rest of the regions are above 1 time/year. The annual average frequency of stronger cold air in most parts of the country is between 2 and 3 times/year, and its high frequency areas are mainly located in the eastern coastal areas, with an annual average of 3 to 4 times/year.

The annual average frequency of strong cold air is significantly less than that of general cold air. The Qinghai-Tibet Plateau-Hertau region - Northeast area and the eastern coastal area are relatively high frequency areas for strong cold air, while the Tarim Basin, Sichuan Basin and Yunnan area are less than 0.5 times/year.

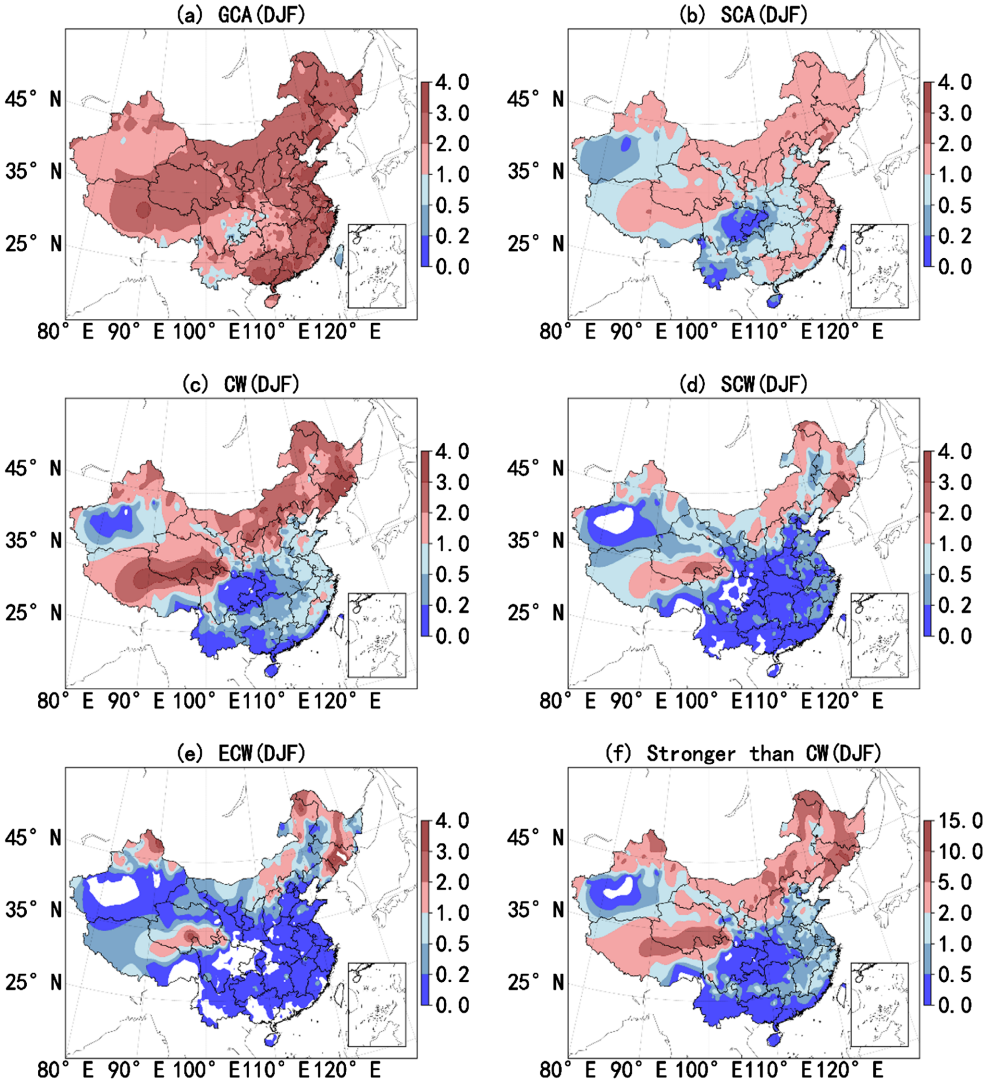

Figure 2. Spatial distribution of the average frequency of different levels of winter cold events from 1960 to 2020, Unit: times. (a) General cold air; (b) Strong cold air; (c) Cold wave; (d) Strong cold wave; (e) Extreme cold wave; (f) Stronger then cold wave.

Compared with strong cold air, the frequency of cold wave cold air activity in the south is significantly reduced, with significant differences between the north and the south, showing the characteristics of more in the north and less in the south. The northeast, north and northwest China and the Qinghai-Tibet Plateau are the high frequency areas for cold wave cold air activity, with an annual average of 1 - 4 times/year, while the eastern plateau (southern Ningxia and eastern Tibet) and the southern northeast are the high frequency centres, with 3 - 4 times/year. 4 low frequency areas are located in the Tarim Basin, the Sichuan Basin, southern Liangguang and southern Yunnan, with an annual average frequency of less than 0.2 times/year. Cold waves are less frequent in southern China south of 25˚N, mostly below 1 time/year, with northern Fujian and southern Zhejiang being the relative high frequency centres of cold wave cold air activity in the southern region, at 1 to 2 times/year. This is consistent with the findings of Qian and Zhang (2007) that a zone of high frequency cooling events also exists south of the Yangtze River.

The frequency distribution of strong cold wave is similar to the frequency distribution of cold wave, but the overall frequency decreases, the high frequency centre is located in southern Qinghai and southern Jilin, the annual average frequency in the southern region is less than 0.5 times/year, the Sichuan Basin and Tarim Basin have not experienced strong cold wave weather in the past 61 years.

The annual average frequency of extreme cold waves in most parts of the country is less than 0.2 times/year. Northern Xinjiang, central-eastern Inner Mongolia, southern Qinghai and southern northeast China are high frequency areas for severe cold wave activity, with more than 1 time/a. Southern Jilin has the highest number of extreme cold waves, with an annual average of more than 4 times. The frequency of super cold waves in the Sichuan Basin, Tarim Basin, western Yunnan and southern Guangdong is 0. The Northeast Plain is a relatively low frequency area for extreme cold waves in the Northeast.

In this paper, general cold air and strong cold air events are referred to as general cold events, and cold wave, strong cold wave and extreme cold wave are referred to as severe cold event. In summary, it can be found that there is little difference in the distribution of the frequency of general cold events from north to south, with the central-southwest China and Xinjiang regions being relatively low frequency areas for general cold events in China. The frequency of severe cold events in China is more in the north than in the south, with northeast China, Inner Mongolia, Qinghai and Tibet being the high frequency areas of severe cold events in China, while the frequency of severe cold events in eastern China to the south and east of these areas is significantly reduced. In addition to latitude, cold event is closely linked to topography. Basins surrounded by high mountains are difficult to be affected by cold event, especially severe cold events.

3.1.2. The Frequency of Cold Events in December

In order to further analyze the characteristics of cold air affecting China in winter, this paper calculates the spatial distribution characteristics of the average

frequency of different levels of cold events occurring month by month in winter from 1960 to 2020, the overall distribution pattern is basically the same, but there are certain differences. In December (Figure 3), General cold air mainly affected the central-eastern part of China except Xinjiang, the Sichuan basin and the Yunnan-Guizhou plateau, with an annual average frequency of 0.8 to 1.4 times/year, among which the eastern coast was a high frequency area for general cold air, at more than 1 time/year.

The annual average frequency of strong cold air is significantly reduced compared to that of general cold air, with the Qinghai-Tibet Plateau, the Loop and the northeast area and the eastern coastal region still being relatively high frequency areas, but the average frequency is also less than 0.8 times/year. Similar to the winter cold wave frequency distribution type, December cold wave cold air frequency is also significant differences between the north and south, north more south less characteristics. The frequency of strong cold waves and extreme cold waves in December is generally low, with an annual average frequency of

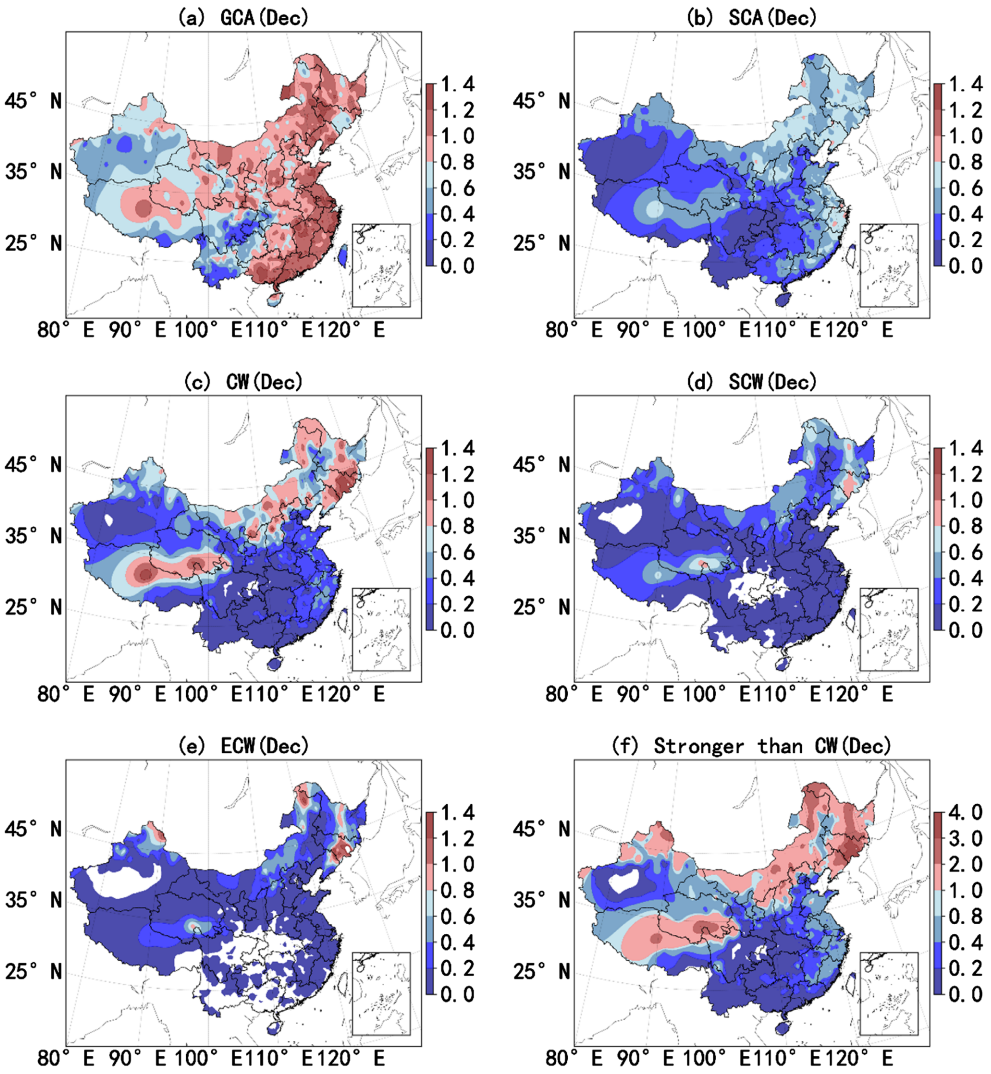

Figure 3. The same as Figure 2 but for December.

less than 0.4 times/year in most parts of the country, with strong cold waves in addition to the two high frequency centres mentioned above, there were also two high frequency centres of 1.4 times/year in northern Xinjiang and northeastern Inner Mongolia.

3.1.3. The Frequency of Cold Events in January

In January (Figure 4), the distribution of the frequency of general cold air was similar to that of December, with less general cold air and less stronger cold air than in December, especially in the central and western regions where the annual average frequency of general cold air was about 0.4 times/year less than in December, with the central and eastern regions being the high frequency area, gradually decreasing to the west, with the annual average in the northeast as well as the eastern coastal regions, with the annual average frequency in the range of 0.8 to 1.0 times/year, and the strong cold air The high frequency area is still located in the Qinghai-Tibet Plateau - Loop area - Northeast area and the eastern

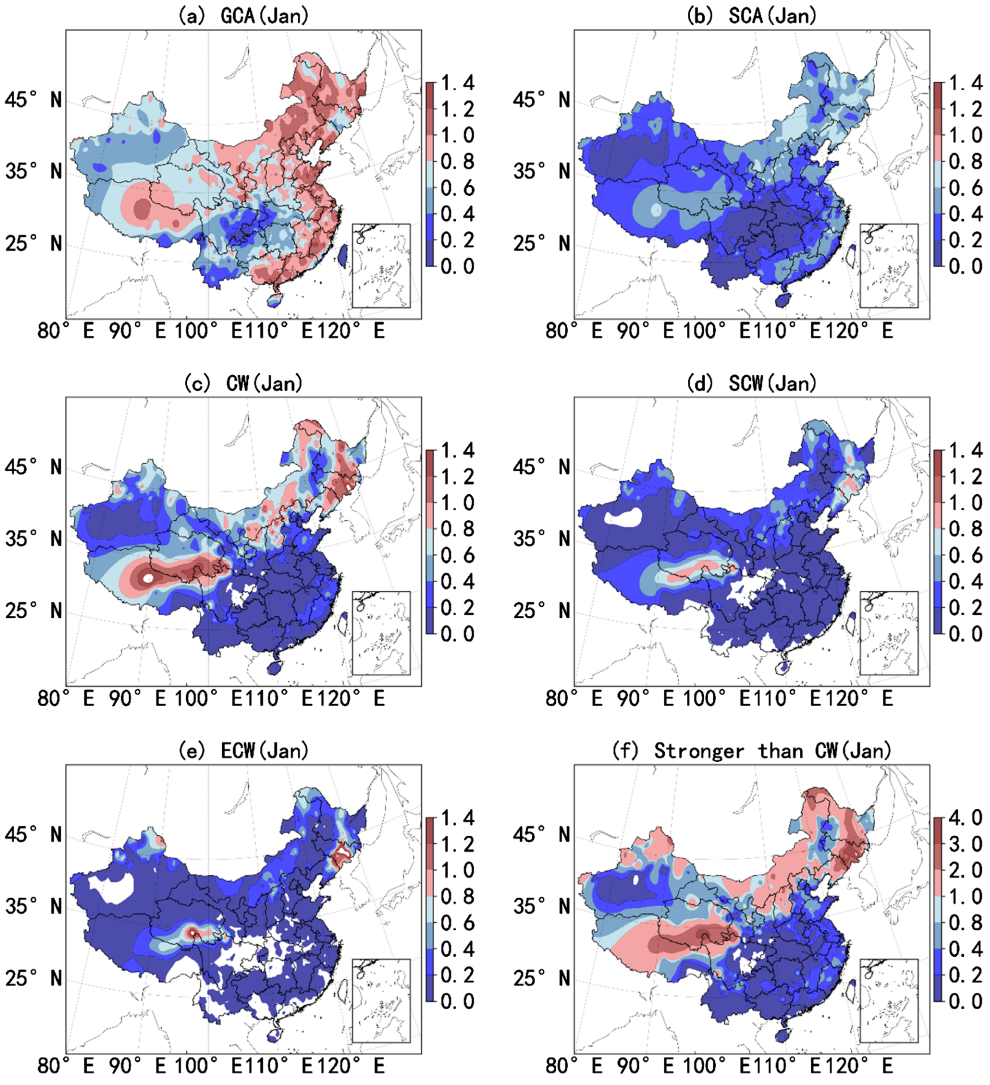

Figure 4. The same as Figure 2 but for January.

coast to the eastern part of South China, with an annual average of 0.4 to 0.8 times/year.

The frequency of cold wave cold is comparable to December in the northern regions, but decreases in the southern regions with an annual average frequency of 0.4 times/year. The frequency of extreme cold waves was significantly higher in the eastern part of the plateau than in December, and the range of strong cold waves that did not occur in the Sichuan basin was reduced. There was a significant centre of large values in the southern part of Qinghai on the eastern plateau, with an annual average frequency of 1.4 times/year or more, and the area of the southern region without a strong cold snap was also decreasing. Overall, the frequency of colder and stronger cold air in January was less than in December, while the frequency of cold wave, strong cold wave and super cold wave cold event in the northern region was comparable to that in December, but in the eastern plateau and the southern region the cold air above the cold wave level was more active.

3.1.4. The Frequency of Cold Events in February

In February (Figure 5), the frequency of general cold air decreased significantly, with the maximum annual average frequency below 1.2 times/year, especially in Xinjiang, Inner Mongolia, North China and Northeast China, with an annual average frequency of less than 0.8 times/year, with the maximum high frequency centre located in eastern Guangxi and the western part of Guangdong, but cold air above the level of cold wave decreased in South China, with no strong cold wave in South China's coast and southern Yunnan in February There was no strong cold wave or super cold wave in February.

3.2. The Duration of Cold Events in Winter

The frequency distribution characteristics of different levels of cold event processes have been analyzed above, and the different levels of cold air can indirectly reflect the changing characteristics of cold event intensity. However, the frequency of cold event is only one aspect of a cold event. The duration and magnitude of minimum temperatures are also important indicators of the intensity of the cold event. In the following, the intensity of cold events in China during winter is discussed by examining the duration and magnitude of minimum temperatures of cooling events.

Figure 6 gives the average cooling duration of single-station severe cold event in winter and in-season months from 1960 to 2020. It can be found that the overall average cooling duration of single-station severe cold event is greater in the south than in the north, with the longest duration lasting in eastern Guangxi, Guangdong, southern Hunan, southern Jiangxi and eastern Guizhou, and the average single strong cooling event can last 3 to 3.5 days in the north. The duration of cold air is shorter than that of the southern regions, except for the northeastern part of Xinjiang where the average duration can be more than 3 days, the average duration of most regions is 1.5 - 2.5 days, and the Qinghai-Tibet

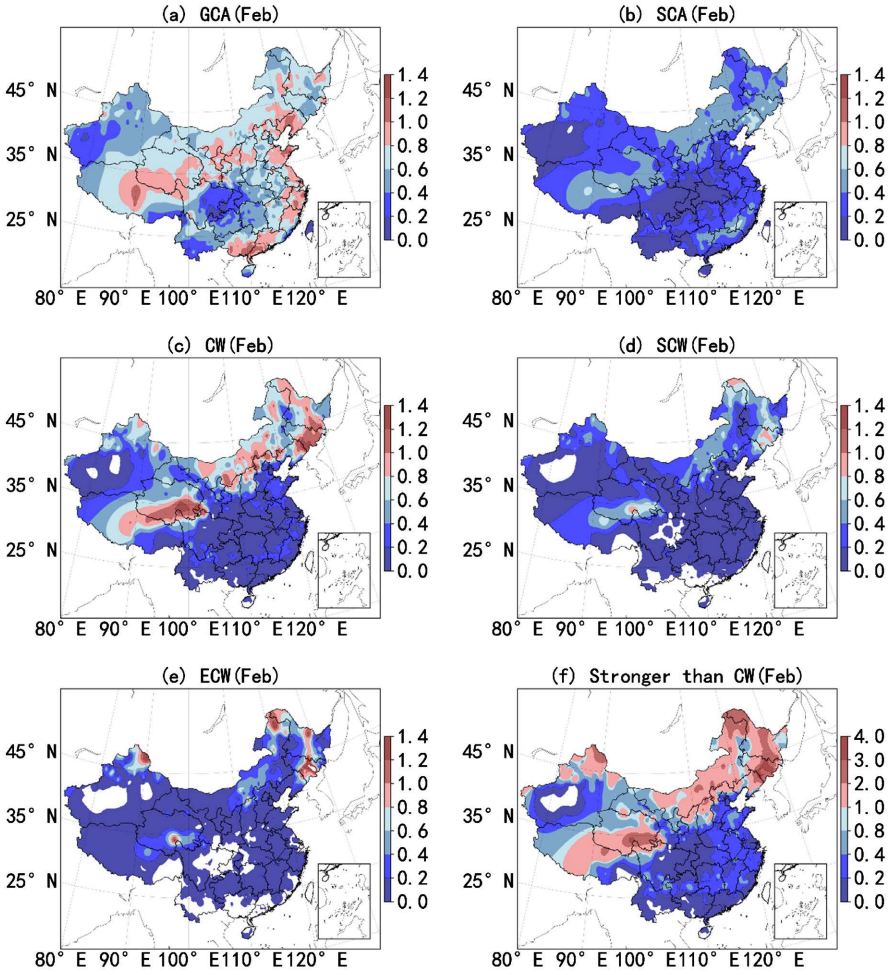

Figure 5. The same as Figure 2 but for February.

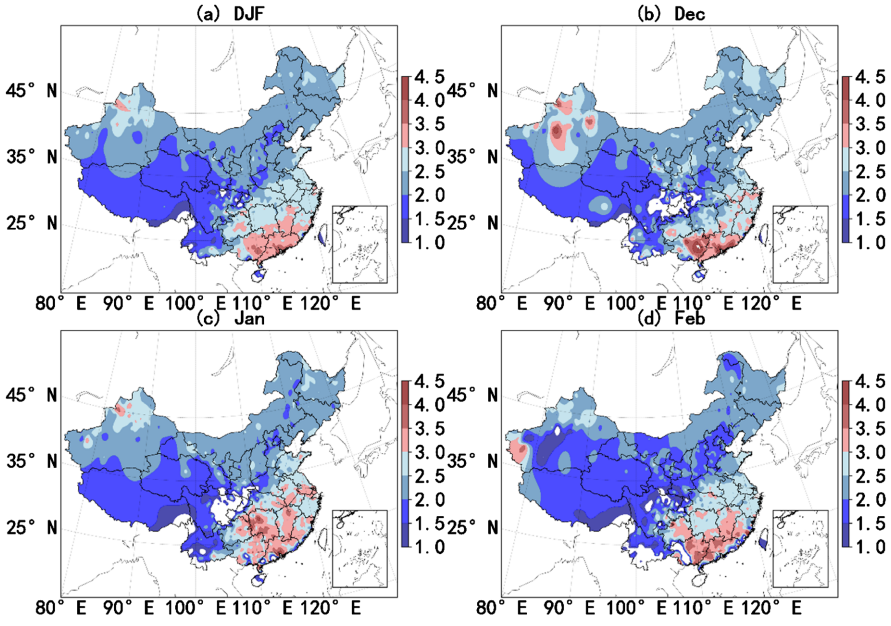

Figure 6. Average duration of severe cold events in winter and each month during the season from 1960 to 2020 (unit: day). (a) Winter; (b) December; (c) January; (d) February.

Plateau is the region with the shortest duration of severe cold event in China, with an average duration of 1.5 - 2.0 days. In terms of the month-by-month average duration of single-station cooling in winter, December has the longest overall average duration of single-station cooling, followed by January and the shortest in February, whiles severe cold events last longer in Jiangnan in January, reaching 3.0 to 3.5 days.

The average duration of a single station of a general cold events (Figure 7) is similar to the spatial distribution of the duration of severe cold events, showing a situation of long duration in the south and short duration in the north, with Guizhou, Guangxi, Guangdong, Jiangxi and southern Hunan having a longer average duration of 3.0 - 3.5 days, while most areas north of the Yangtze River lasted less than 3 days so far, except for local areas in northwest Xinjiang, which lasted up to 3 days. The general duration of general cold events in northern areas is longer than that of severe cold events, while the opposite is true in the south. In terms of month-by-month distribution, similar to the duration of severe cold events, December remains the month with the longest duration of cold winter air, followed by January and the shortest duration in February.

And in terms of maximum cooling duration, for severe cold events (Figure 8), the longest duration was under 9 days, with the longest duration in most parts of the country ranging from 5 to 7 days, except for the Sichuan Basin and Yunnan areas in the eastern Qinghai-Tibet Plateau, where it was under 5 days. Similar to the average duration, December remained the month with the longest duration of cold air activity, with the shortest duration in February.

The longest duration of general cold events is longer compared to that of a

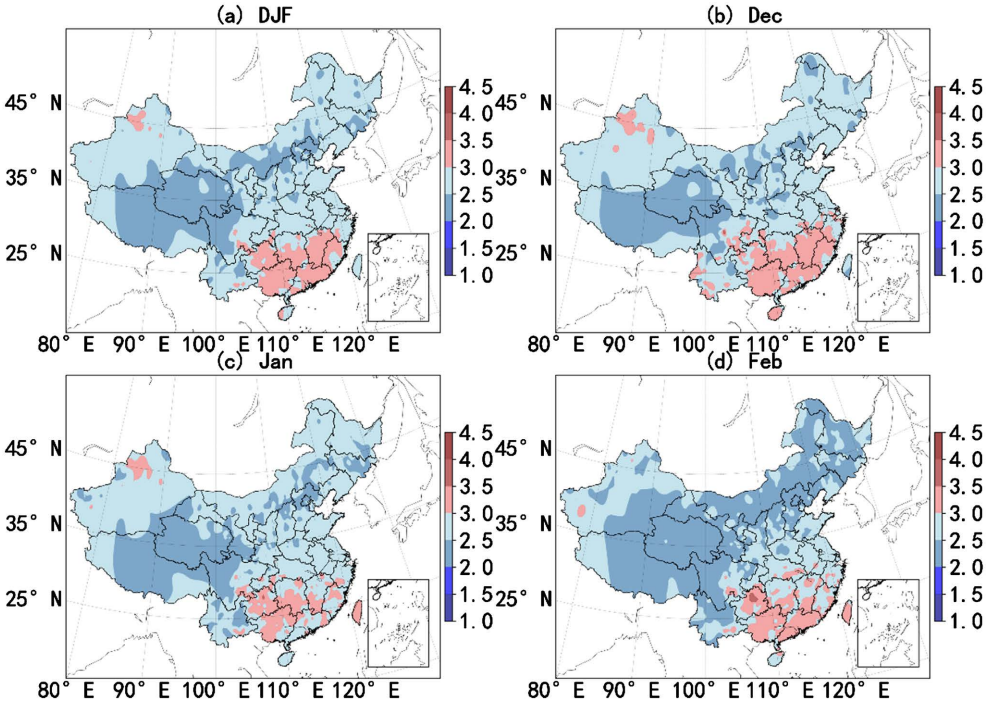

Figure 7. The same as Figure 6 but for general cold events.

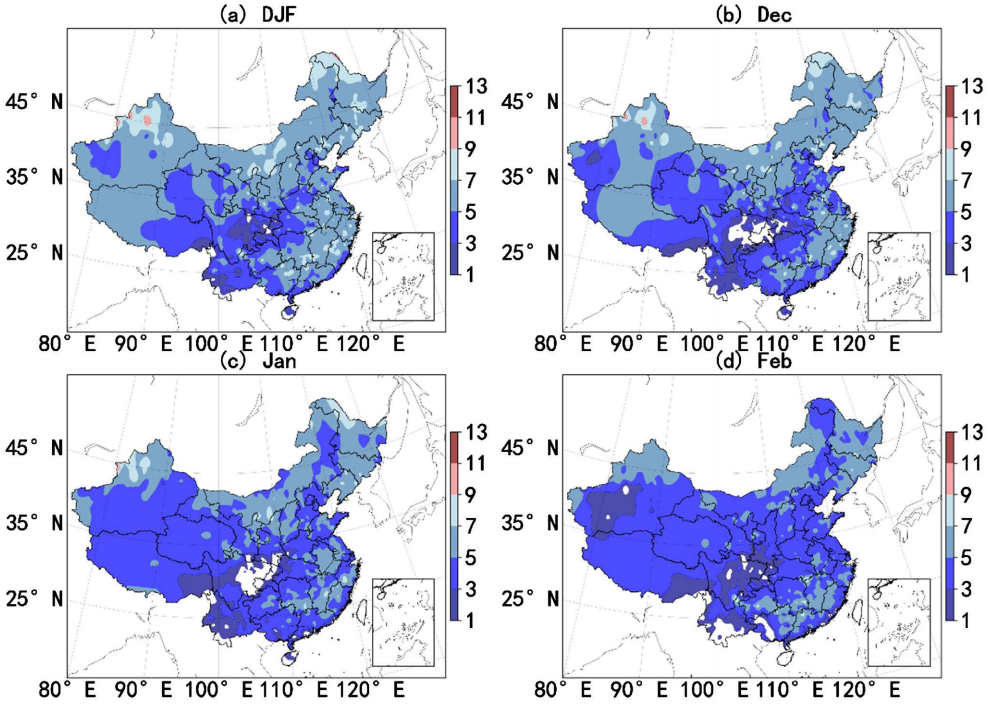

Figure 8. Maximum duration of severe cold events in winter and each month during the season from 1960 to 2020 (unit: days). (a) Winter; (b) December; (c) January; (d) February.

strong cooling event, and varies widely from north to south, with the area around the southern ridge of South China remaining the longest cold air activity, with continuous cooling of up to 13 days, and December remaining the longest duration, with northern regions having comparable January and December and the shortest February; southern regions having the second longest February and the shortest January duration (**Figure 9**).

3.3. Maximum Temperature Reduction during Cold Events

Figure 10 gives average maximum cooling range of single station severe cold events in winter and each month during the season from 1960 to 2020. It can be seen that the average maximum cooling in winter is above 11˚C, except for the Qinghai-Tibet Plateau, the Sichuan Basin, the southern part of the Loop and Yunnan, where it is less than 11˚C. In general, the average cooling in the south is greater than that in the north, and the average cooling in southern China is above 12.5˚C, with the centre of the maximum being in the Guangxi region between eastern Guangxi and western Guangdong, reaching 17˚C. Northern Xinjiang and Northeast China are the next largest centres of average cooling in the distribution map, at 12.5˚C or more. In December (**Figure 10(b)**), the area with a cooling range above 12.5˚C contracted to southern China and Fujian, with an unusually large average maximum cooling range of 18.5˚C in western Guangdong and eastern Guangxi. In January (**Figure 10(c)**), the average maximum cooling range increased to above 12.5˚C in the middle and lower reaches of the Yangtze River. The strong centre in southern China weakened, with the maximum

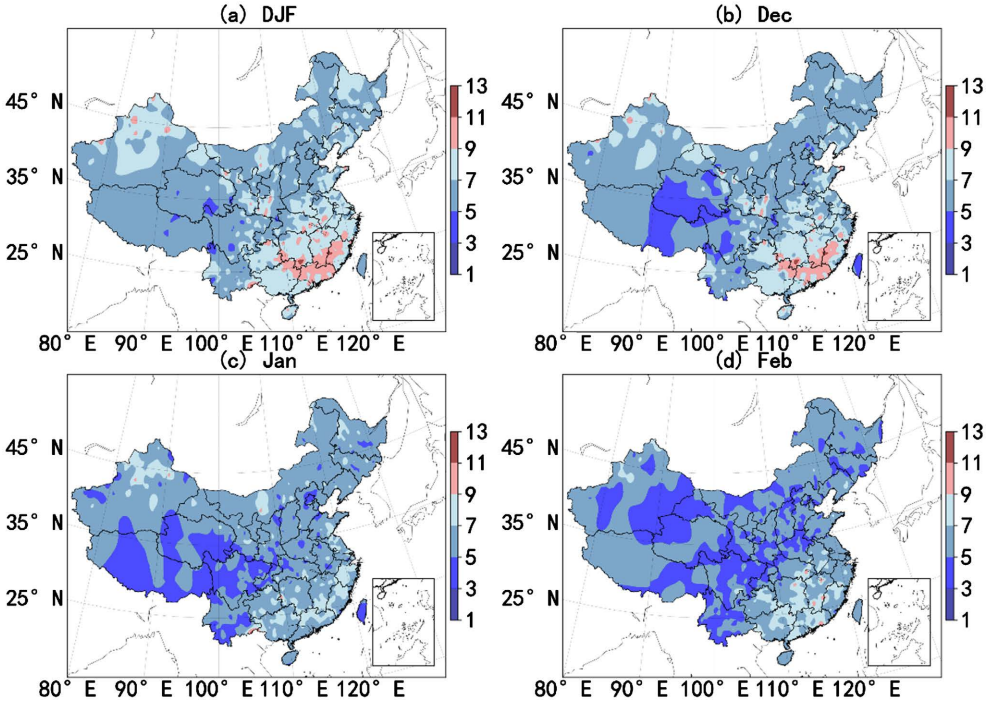

Figure 9. The same as **Figure 8** but for general cold events.

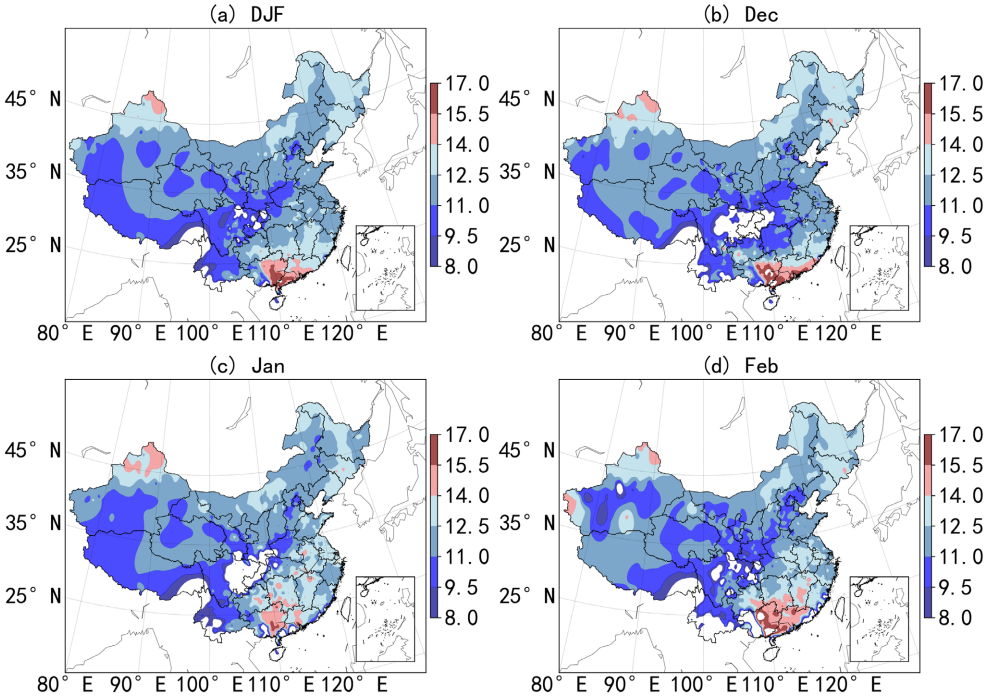

Figure 10. Average maximum cooling range of single station severe cold events in winter and each month during the season from 1960 to 2020 (unit: ˚C). (a) Winter; (b) December; (c) January; (d) February.

mean cooling centre weakening to 17.0˚C. Regional differences in cooling amplitude in southern regions decreased. February (**Figure 10(d)**) saw the strong

centre in southern China expand in extent and increase in intensity.

3.4. Temporal Variation of Cold Events in Winter

Figure 11 shows the linear trend in the frequency of general and severe cold events in China between 1960 and 2020 in winter. The frequency of severe cold events decreases linearly over most of the country except for the Loop and Qinghai-Tibet Plateau, and is most pronounced in northeast China and eastern Xinjiang, with a local linear trend of 0.05 times/year. This is slightly different from Qian and Zhang (2007) who noted that the trend of decreasing cold wave events is mainly concentrated in Xinjiang, North, Northeast and East China, which may be related to the different definitions in this paper.

3.5. Variation of Regional Severe Cold Events

Statistics found (Figure 12) that 147 severe cold events have occurred in winter in China over the last 61 years, with an average of 2.4 events per year. According to the definition of southern-type severe cold events, no regional severe cold events affecting the south alone have occurred in the past 61 years. Therefore, this paper actually divides the winter severe cold events from 1960 to 2020 into two categories for study, i.e. China national severe cold events and northern severe cold events. 45times of China national severe cold events have occurred in the past 61 years, with an annual average of 0.7 times. January is the next most frequent month, with 14 times, and February is the least frequent month, with only 9 occurrences. In terms of interannual distribution, there is a decreasing trend in national severe cold events over the last 61years, with a linear trend coefficient of −0.01 events/year. In terms of interdecadal distribution, national severe cold events were more frequent in the 1960s to 1970s, less frequent in the 1980s to early 21st century, and increased again after 2008. Over the last 61 years, 102 times of northern-type severe cold events have occurred in winter in China, with an average of 1.7 events per year. Statistics on the frequency distribution of regional severe cold events in each month reveal that, similar to the monthly

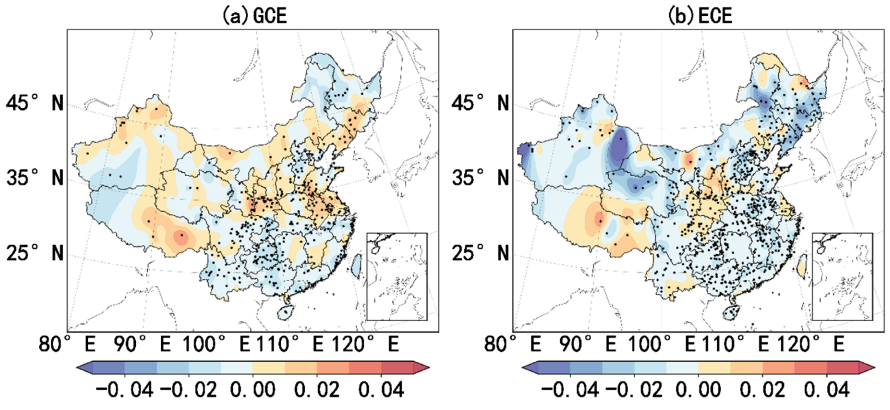

Figure 11. Spatial distribution of linear trends in the frequency of general cold events (a) and severe cold events; (b) in winter from 1960 to 2020 (dot area pass the significance test of $\alpha = 0.05$).

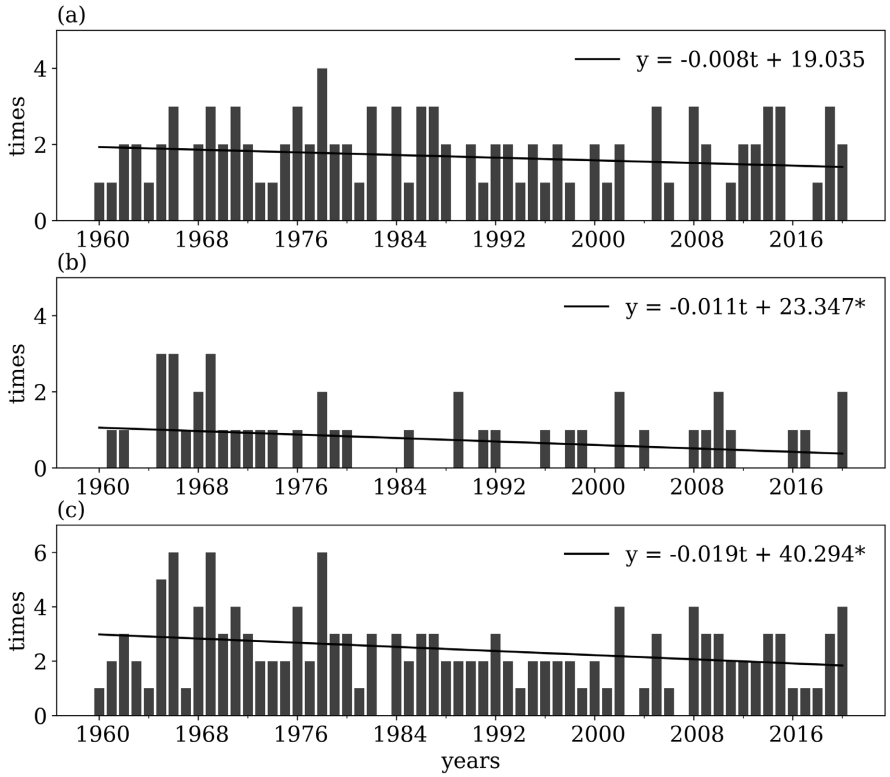

Figure 12. Annual change in frequency of winter northern (a), national (b) and total severe cold events (c) from 1960 to 2020.

distribution of total cold event frequency, December has the most frequent regional severe cold events, with 45 occurrences over the last 61 years, accounting for 44% of the number of regional severe cold events in winter, followed by February and the least in January.

4. Conclusion

This paper analyzes the characteristics of cold events affecting China by classifying it into five different classes using daily values of ground station elements for a total of 61 winters from December 1960 to February 2021, to enhance the activity pattern of cold air in the context of global warming, which is of great significance for the forecast of cold air and the reduction of meteorological disasters caused by cold air with the following main conclusions:

1) The frequency of general cold events does not differ greatly from north to south, with the central-southwest China and Xinjiang regions being the relatively low frequency areas for general cold events, with the highest frequency in December. The frequency of severe cold events in China is more in the north than south, and the high frequency of severe cold events is in Northeast China, Inner Mongolia, Qinghai and Tibet. The frequency of severe cold events varies little from month to month in the north, but in the eastern plateau and the south, it is more active in January. The basin is hardly affected by cold air, especially strong cold air.

2) The average duration of cold events is greater in the south than the north. The average duration of general cold events is longer than severe cold events in the north, while it is the opposite in the south. Cold events last the longest in December and the shortest in February. The average cooling in the south is greater than in the north, with the centre of the maximum located in southern China.

3) In the last 61 years, general cold events have increased in most of the northern part of the country and decreased mainly in the Yunnan-Guizhou Plateau and southern China. But severe cold events have been decreasing linearly in most parts of the country.

4) Severe cold events affecting China can be divided into China national-type and northern-type, of which there are significantly more northern-type than China national-type, with 45 national-type events occurring in the past 61a, and 102 northern-type events occurring.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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