The dominant invading paths of extreme cold surges and the invasion probabilities in China

Ting Ding | Hui Gao | Yuan Yuan

Climate Prediction Division, National Climate Center, China Meteorological Administration, Beijing, China

Correspondence
Hui Gao, Climate Prediction Division, National Climate Center, China Meteorological Administration, Beijing, China.
Email: gaohui@cma.gov.cn

Abstract
Based on daily temperature observation dataset with high quality and spatial resolution, this paper revealed the dominant invading paths of the extreme cold surges (ECSs) within China by using the fifth percentile of temperature drops instead of the traditional unified threshold in the operation. The maximal probabilities of the ECSs from the upstream regions to the downstream regions along the invading paths are also provided. Results indicate the distribution of the fifth percentile is quite different in various regions, with the highest value centers of more than 8°C in northern China, and a secondary center of 6–7°C in southern China. While in the areas between the Yellow River basin and the Yangtze River basin, the two longest rivers in China, the values are below 5°C. This result explains the unreasonable frequency gap between the two rivers in previous unified threshold. Based on the distribution, the whole country is roughly divided into 18 regions at an approximate box of 5°N × 10°E to acquire clear and objective invading paths by the lead–lag correlation analysis and an objective identification of the paths. Results show the ECS invading path in northern China has a dominant west or northwest track. But in southern China, the invading paths are more complex, generally from north to south. In China, about 30–40% ECS cases in the upstream regions can lead to the ECSs in the downstream regions along the dominant paths. By the identification and the lead–lag correlation, northwestern China could be regarded as the source of ECSs invading other regions.

KEYWORDS
China, extreme cold surge, invading path, probability

1 | INTRODUCTION

Cold surge (CS), which describes a rapid temperature drop (TD, much colder than a previous day), is a common weather phenomenon in the winter season. The extreme CS (ECS) events are the most severe meteorological disasters in Northern Hemisphere (NH). Despite the global warming trend, ECSs or severe cold winters occurred frequently in mid-latitudes of Eurasia and North America over the past decade. Based on five different global datasets, Li et al. (2015) pointed out the global mean surface temperature (GMST) trend in the...
period 1998–2012 was strongly influenced by a pronounced Eurasian winter cooling trend. During the so-called hiatus period of the GMST, both summertime warm and wintertime cold extreme occurrences increased overland (Johnson et al., 2018). Besides above observed statistic facts, many severe ECS cases in recent several years also supported the conclusion, including the cold spell in 2012/2013 winter in Europe (Vries et al., 2013; Planchon et al., 2015), the severe winter events in North America (Trenary et al., 2016; NWS, 2019), and the record-breaking ECS in January 2016 (ECS2016) over East Asia (Ma and Zhu, 2019; Yamaguchi et al., 2019).

In East Asia, the climate in winter is deeply influenced by the East Asian winter monsoon (EAWM) system. During the EAWM period, the significant pressure gradient between the Siberian high (SH) and the Aleutian low (AL) causes the outbursts of strong northerly winds along eastern China, Korea, and Japan, and leads to sharp TD in the region (Hao et al., 2016; Wu and Sun, 2017). ECS events can even affect the tropical regions of Asia by bringing severe cold and snowy weather under certain EAWM modes (Peng and Sun, 2017). Mainly influenced by the Arctic warming or the sharp decrease of the sea ice, the cold winters or ECS events in East Asia have inconsistent trend with the GMST in the recent decade (Kug et al., 2015; Li et al., 2015; Wu et al., 2017; Dai et al., 2019; Ma and Zhu, 2019). For example, the ECS2016 mentioned above swept through East Asian and Southeast Asian countries. During this event, about 71% territory of China and 710 million people were affected by a minimal temperature lower than −12°C (CMA, 2017). The snowline even reached Guangzhou and the Pearl River Delta in southern China, the lowest latitude of snow recorded in China since 1951 (Qian et al., 2018). Snowfall was also observed for the first time in recent 115 years at Amami-Oshima, Japan (Yamaguchi et al., 2019). The ECS2016 also caused 14 human deaths in Thailand and led to the first-ever snowfall over northern Vietnam (Ma and Zhu, 2019).

For quite a long history, ECS events have drawn considerable attention in both public and research communities in East Asia, especially in China. Even in the warmer future, ECS occurrences will remain frequent and will be independent of the increasing GMST (Park et al., 2011; Zhu et al., 2018). Therefore, the understanding of the ECS invading tracks is crucial to the forecast and the disaster mitigation. As early as 1959, Tao (1959) summarized the cold air source regions and discovered three main invasion paths that affected China based on the forecast experiences, including the northwest path that intrudes into eastern Europe from the Barents Sea and into China through Siberia and Mongolia, the polar path that moves from the Kara Sea to Siberia and then attacks China, and the north–south path that moves from the east areas of Lake Baikal. Ding and Krishnamurti (1987) investigated the heat budget of the SH based on 19 strong cases moving over China from its northwest region in five winters of 1980–1984, and also explored three major tracks of the SH that traversed China. The most frequent track has a northwest moving path and this type can account for about 64% of all the cases. The second most frequent track has a percentage of 27% and moves eastward from Xinjiang province to the western part of Mongolia and finally arrives over eastern China, or moves toward southwestern China along the eastern periphery of the Tibetan plateau. The third track mainly affects northeastern China, Korea, and the Sea of Japan, with a percentage of 10%. Zhu et al. (2007) pointed the major CS sources could be tracked to the Barents Sea, the Kara Sea, and the south of Iceland. Wang (2018) summarized the ratio of different cold air track types based on 1,138 cases during the winter of 1970–2013. For the type invading Inner Mongolia and Northeast China, the northwest track has a prevailing contribution, while for the type invading Northwest China, the westward track is the most important. Recently, Cai et al. (2019) found the above invading tracks existed not only in winter season. By analyzing 46 CS cases affecting North China in the autumn of 1961–2014, they explored three typical path types, that is, the north type (12 cases), the west type (16 cases), and the northwest type (18 cases).

As mentioned above, both the attacking track types and the ratio of each type have been explored. However, owing to the limitation of the unified threshold applied to all regions, there is a frequency gap in middle especially between the Yellow River basin (YeRB) and the Yangtze River basin (YaRB; Ma et al., 2009; Ding, 2013). This led to the previous studies focusing mainly on the ECS tracks from high latitudes of NH to northern China, and few outlined the invading paths within the whole country, especially the dominant invading path for a particular area. Besides, all the above studies revealed the ratios or percentages of different track types, but did not mention the invading probabilities of the ECS events from upstream regions to low-stream regions. Therefore, it is necessary to study these questions. Considering the fact that the threshold values of ECSs have significant differences in China, after a brief introduction of dataset in Section 2, we display the threshold distribution of ECSs in winter time in Section 3 based on the individual fifth percentile of daily TDs instead of a unified value. Section 4 provides the maximal probability of dominant invading paths in China with leading time 1 day. Summary and discussions are listed in Section 5.
2 | DATA AND METHOD

Observed air temperature data at 2,513 weather stations are provided by the National Meteorological Information Center of China (Ren et al., 2012). In this paper, daily mean temperatures at 1,871 stations with complete data in December–February between 1981 and 2019 are used. This dataset has addressed data quality issue and the inconsistency issue between archived datasets at national level and provincial level. Compared to the previous version of dataset of temperature observations, both the quality and spatial resolution (number of stations) of the new dataset have been greatly improved. The dataset has been widely applied to operational meteorological services and scientific studies in China. Considering the fact that the ECSs mainly occur in boreal winter, the analyzing season in this study focuses on December–January–February (DJF). Here the DJF 1981 denotes December 1980–January 1981–February 1981.

For a station, an ECS event here is defined as the daily TD exceeding the fifth percentile of all the TDs in the research period. As ECSs have rapid movement from northwestern China or northern China to southern China, the sharp TDs occurred only in 1 day for most stations. Statistical results indicate the probability is only about 4.8% for TDs exceeding the fifth percentile in two continuous days. So, in this paper, we only focus on the TDs in 1 day.

3 | SPATIAL DISTRIBUTIONS OF THE ECS THRESHOLDS IN CHINA

As mentioned above, ECS event is one of the most hazardous disasters occurring in China during wintertime. According to Chinese National Emergency Plan of Meteorological Disaster and the operational standards in weather forecast departments, a threshold 8°C of daily mean TD is widely used as the criterion of an ECS event. Dots in Figure 1 show the climatological frequency of TD based on this criterion during the winters of 1981–2019. It can be seen that the frequency is quite different in various regions, with more in the north and south of China and less in the middle. Based on this threshold, the highest frequency of ECS events is found in northern China including three centers, with more than 2 times/year in the north part of northwestern China (NWC) and northeastern China (NEC), and 1–2 times/year in the north part of North China (NC). The second highest frequency center of ECSs is located in South China (SC, regions south of 27°N), but the frequency is less than 1 time/year and is much lower than that in northern China. It can also be seen from Figure 1 that the ECS frequency between the YeRB and the YaRB is relatively low with less than 0.5 times/year, especially in the middle and lower reaches of the YaRB with the frequency less than 0.2 times/year (figure omitted). This frequency distribution cannot reasonably illustrate the observed fact that CS especially ECS events invade rapidly southward and affect most parts of central and eastern China. It is also difficult to explain why SC is the second highest frequency center of ECS events, but low frequency is found in the regions between the YeRB and the YaRB. This gap is partly related to the variance gap between the two rivers. Lots of cases validated that ECSs invaded eastern China through this gap, such as the extraordinarily freezing disaster in 2008 (Wen et al., 2009), the severe snow and cold event in 2018 (Peng and Sun, 2019).

**FIGURE 1** Climatological distributions of the ECS thresholds at the fifth percentile (shades, °C) and the frequency of daily TD above 8°C (dots, times/year) during the winters of 1981–2019. The blue contours denote the stations at which the fifth percentile greater than 8°C. The small gray, small black and big black dots denote the frequencies of 0.5 ~ 1, 1 ~ 2 and above 2 times/year. The abbreviations “NWC”, “NC”, “NEC”, “SC”, “YeRB” and “YaRB” in the figure mean Northwest China, North China, Northeast China, South China, the Yellow River basin and the Yangtze River basin, respectively.
To avoid the limitation of the definite threshold 8°C in different regions, Figure 1 also shows the fifth percentile threshold distribution (shades) of the ECS at each station. The distribution of the percentile threshold is also quite different in various regions. Only in the three highest frequency centers mentioned above, the threshold can exceed 8°C, the criterion used in the operation. The fifth percentile threshold of ECS in SC and eastern coastal area is above 5°C, while below 5°C in most of the area between the YeRB and the YaRB. This also indicates that the current ECS standard of 8°C has great spatial limitations, as it applies only for northern regions in China. Even if the threshold decreases to 6°C, it is still difficult to identify the ECS events between the YeRB and the YaRB.

In China the distribution of the observation stations has significant spatial differences, with dense in eastern part and sparse in western part. To acquire clear and objective invading paths of ECSs between different regions, the whole country is roughly divided into 18 regions at an approximate box of 5°N × 10°E in the following study based on the thresholds explored by Figure 1 and other meteorological geographic information. The fifth percentile threshold of ECS for each region is given in Figure 2. The distribution is similar with that in Figure 1. The largest threshold exceeding 5°C is found in central and eastern Inner Mongolia and NEC (Regions A03, A04, A05, and A06 in Figure 2). Thresholds in eastern coastal areas from northern China to southern China (Regions A10, A14, A16, and A18) are greater than those in their west regions, with a value between 4 and 5°C. This is mainly because they are easily affected by the EAWM, and the low altitudes in these regions are conducive to the cold air intrusion, resulting in large TD ranges. Though the CSs from the polar areas to China arrive in northern Xinjiang and western Inner Mongolia (A01 and A02) first (Ding and Krishnamurti, 1987), the thresholds in these two regions are lower than those in their east at the same latitudes, with values of 3–4°C. This is due to the climatological southerly winds in these two regions, while the northerly winds of the EAWM prevail in eastern China. The thresholds of ECSs in the rest regions are below 3°C owing to the blocking roles of the high topography of the Tibetan Plateau.

4 | DOMINANT INVADING PATHS OF ECSs IN CHINA

Lead–lag correlation analysis is a common method to reveal the asynchronous variation of a variable in different regions. To explore the possible influencing paths, the 39-year averaged lead–lag correlation coefficients (CCs) of daily mean temperature changes in wintertime among the 18 regions are calculated and displayed in Figure 3. The region numbers in the vertical axis are 1 day ahead of the regions in the horizontal axis. From Figure 3 it could be found that almost all the significant CCs exist in the bottom right side of the diagonal line. This distribution reveals a basic fact that the temperature variations in China are mainly affected by the temperature changes from the west and north sides. Generally speaking, northwestern China could be regarded as the leading influencing source. But for different regions, the leading correlations are much diverse. Temperatures in northern China (north of 40°N, Region A01–A10 shown in Figure 2) are mainly affected by the counterparts in their west sides. While in southern China, the leading influencing paths are far more complex than those in northern China. In these regions (A13–A18) temperatures can be affected by the counterparts both from the northwest road and from the north road, but the north road plays a more significant role. Prevented by the plateau in the north side, the temperatures in Tibet (A11 and A12) are independent of other regions.

However, the results in Figure 3 are mainly based on the lead–lag correlations of temperature changes, which include both temperature rises and TDs. The results applicable to ECS events need further analysis. Here an objective identification of the dominant invading paths of ECSs in different regions is applied.

If there is a dominant ECS invading path from upstream area Q to low-stream area P, it can be considered that an ECS event is very likely to occur firstly at Q and then a day later occur at P with a high probability. For area P, all its ECS cases are obtained by using the fifth percentile threshold of temperature drops from 1 day to the next day. For area Q in the

**Figure 2** The ECS thresholds (°C) of the fifth percentile for 18 regions (A01–A18) in wintertime
upstream of the ECS invading $P$, by the same method all its ECS case number is $N$, and the case number 1 day before the occurrence at area $P$ is $M$. Then the probability is defined as the ratio of $M$ to $N$, that is, $p = M/N \times 100\%$.

For all the ECS events at area $P$ (day 0), the probability of ECS events occur at area $Q$ 1 day early (day −1) is written as $p(P^0, Q^−1)$. Similarly, for all the ECS events occurred at area $Q$ (day 0), the probability of ECS events at area $P$ 1 day later (day +1) is written as $p(Q^0, P^+1)$. Here the superscripts $0$, $−1$, and $+1$ of $P$ and $Q$ mean the ECS occurring day, 1 day before the occurring day, and 1 day after the occurring day. The subscripts mean areas.

For area $P_1$ and $Q_1$, the path $Q_1P_1$ is considered as the dominant invading path only if one of the following four criteria are satisfied:

1. $p(P_1^0, Q_1^{−1})$ is the maximum of all the $p(P_1^0, Q^−1)$ and $p(Q_1^0, P_1^{+1})$ is also the maximum of all the $p(Q_1^0, P^{+1})$ (shown as the first type in Figure 4a);
2. $p(P_1^0, Q_1^{−1})$ is the maximum of all the $p(P_1^0, Q^−1)$, while $p(Q_1^0, P_1^{+1})$ is not the maximum of all the $p(Q_1^0, P^{+1})$, but $p(Q_1^0, P_1^{+1})$ exceeds a certain threshold, for example, 20% (shown as the second type in Figure 4b);
3. $p(P_1^0, Q_1^{−1})$ is not the maximum of all the $p(P_1^0, Q^−1)$, but $p(Q_1^0, P_1^{+1})$ is the maximum of all the $p(Q_1^0, P^{+1})$, and $p(P_1^0, Q_1^{−1})$ exceeds a certain criterion (shown as the third type in Figure 4c);
4. Both $p(P_1^0, Q_1^{−1})$ and $p(Q_1^0, P_1^{+1})$ have exceeded the certain criterion though neither is the maximum (shown as the fourth type in Figure 4d).

In this study, the probability threshold is 20% for 1-day leading.

For all the 18 regions in Figure 2, above identification method is adopted to obtain the dominant invading paths of ECS events from one region to another in China with a 1-day leading time (Figure 5). The results are similar to the conclusion explored in Figure 3. For the ECSs in northern China, the invading path has a dominant west or northwest track. The probabilities of the invasion are mainly between 30 and 40%, which means in northern China, along the invading path about 30–40% ECS cases in the upstream regions can lead to the ECSs in the downstream regions. The probabilities even decrease in the northernmost part of China, with a value of 15–30%. An exception is North China (A10), in which region about 40–50% ECSs can be traced to the western Inner Mongolia (A03). Different from northern China, the sharp TDs in southern China especially in the southeastern part mainly propagate from their north areas, that is, the dominant invading path is from north to south in these regions. Probabilities are mainly above 30% in these regions, similar to the values in northern China. Previous study revealed that the ratio of the cold air along the northwest path and the west path is about 2:1, but the ratio is mainly obtained from the ECSs invading the whole country from high latitudes in NH (Ding and Krishnamurti, 1987). For different regions in China, the present statistical results indicate the propagating directions and the ratios have obvious spatial differences. Results in Figure 5 also indicate that northwestern China could be regarded as the source of ECSs invading other regions.
Typical events such as the severe cold extreme in 2016 are also considered to validate the invading paths in Figure 5, and the case analysis is consistent with the results of this paper (figures not shown). Similar with Figures 3 and 5, the CCs and the probabilities are also calculated between different regions with a lagging time of 2 days. Compared with Figure 3, the CCs in a 2-day lagging time decrease clearly. The probabilities also decrease remarkably compared with Figure 5, and the possible invading paths are restricted to limited areas in northwestern China. That means for most regions in China, the main influencing time is 1 day.

5 | CONCLUSION

ECS event is one of the most severe meteorological disasters in China. Mainly owing to the Arctic warming, or a related phenomenon named the Arctic amplification, the ECS in China occurred frequently in recent years, and
this is inconsistent with the variation of severe cold winters in mid-latitude regions in Eurasia and North America. Therefore, both the scientific research and the operational forecast of ECSs have drawn considerable attention in China, especially the attacking tracks from high latitudes. However, owing to the frequency gap between the Yellow River and the Yangtze River caused by the unified threshold in whole country, the ECS tracks in the previous studies were mainly focused on northern China. Besides, probabilities of the ECS event from an upstream region to a low-stream region along the invading path were not illustrated. Therefore, based on daily temperature observation dataset with high quality and resolution issued recently by China Meteorological Administration, this paper first revealed the spatial distribution of the threshold at each individual station by using the fifth percentile of TDs instead of the traditional unified value. Results indicate the distribution of the percentile is quite different in various regions, with the highest value centers of more than 8°C in northern China, and a secondary center of 6–7°C in southern China. While in the areas between the YeRB and the YaRB, the values are below 5°C. This result explains why there was a frequency gap in previous studies.

Based on the distribution of the ECS threshold and other meteorological geographic information, the whole country is roughly divided into 18 regions at an approximate box of 5°N × 10°E to acquire clear and objective invading paths. Besides the lead–lag correlation analysis for 1 day leading, an objective identification of the paths is also proposed and applied in this paper by considering four possible leading and lagging invasion probabilities. Results show the ECS invading path in northern China has a dominant west or northwest track. But in southern China, the paths are more complex, generally from north to south. In China, about 30–40% ECS cases in the upstream regions can lead to the ECSs in the downstream regions along the dominant paths. By the identification and the lead–lag correlation, the results reveal that northwestern China could be regarded as the source of ECSs invading other regions.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

ORCID

Ting Ding https://orcid.org/0000-0002-6953-6853

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