The Extended Period Precursory Signals of Strong Persistent Freezing Rain and Snow Events in Southwest China

Xiaojuan Sun

Nanjing University of Information Science and Technology

Siyan Li (✉ m13736872105@163.com)

Nanjing Xinda Institute of Meteorological Science and Technology <https://orcid.org/0000-0002-3369-9618>

Julian X.L. Wang

NOAA Air Resources Laboratory

Yaqing Yang

Jilin Changbai Mountain Meteorological Bureau

Li Chen

Nanjing University of Information Science and Technology

Research Article

Keywords: freezing rain and snow events, extended period warning signs, extension-period forecast, southern China

Posted Date: September 21st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-904186/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

**The extended period precursory signals of strong persistent freezing rain
and snow events in southwest China**

Sun Xiaojuan,^a Li Siyan,^b , Julian X.L. Wang^c, Yang Yaqing,^d Chen Li,^a.

^a *Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research
Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and
Evaluation of Meteorological Disasters (CIC-FEMD) , Nanjing University of Information Science &
Technology Nanjing 210044,China*

^b *Nanjing Xinda Institute of Meteorological Science & Technology, Nanjing 210044, China*

^c *Air Resources Laboratory, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA*

^d *Jilin Changbai Mountain Meteorological Bureau, Jilin 133613, China*

Corresponding author: Li Siyan, m13736872105@163.com

ABSTRACT

In this study, daily temperature and precipitation data between 1950 and 2018 from 753 stations from National Meteorological Information Center, and NCEP/NCAR reanalysis data were used to screen freezing rain and snow events that occurred in the winters of 1951–2017 in southwest China (100°E–110°E, 22.5°N–32.5°N), in order to search for extended period warning signs of events. The combined anomalies index P_{CA} , established by the Mongolian Geopotential height pressure intensity, north–south position index and the southern trough intensity index, is closely related to the freezing rain and snow events in southwest China, and can be used as a link to explore the precursory signals of persistent freezing rain and snow events. The 1000-hPa height field of Iceland (60°N–80°N, 10°W–50°W), the North Atlantic (25°N–45°N; 20°W–60°W) and the Caspian Sea (30°N–50°N; 30°E–70°E) in the early mid-latitude was significantly correlated with P_{CA} . The high disturbance signal in the upstream dispersed to the downstream 15–20 days in advance, which intensified the Mongolian high and deepened the southern trough. The combination anomaly of the Mongolian high and southern trough finally led to the strong persistent freezing rain and snow events in southwest China. The extended period forecast index of strong persistent freezing rain and snow events in southwest China was established according to the average geopotential height of key atmospheric regions 15 days ahead of the event. These findings provide a reference for the prediction of winter disaster events extension-period forecast in southern China.

Keywords: freezing rain and snow events, extended period warning signs, extension-period forecast, southern China.

HIGHLIGHT

Freezing rain and snow weather is a major winter disaster in southern China, and it also happens in other parts of the world. The main purpose of our work is to summarize the regularity of the occurrence of strong freezing rain and snow in South China, and explore its precursor signals (including extension period and cross-season), so as to provide theoretical support for the forecast and prediction of such catastrophic weather. This paper is the second part of our work, which deals with the prediction of the extension period of such catastrophic events.

1. Introduction

Freezing rain and snow weather have a major influence on winter conditions in China, causing adverse impacts on transportation, energy, agriculture, communication, electricity and other aspects of social and economic security. This is particularly the case in southern China, where freezing rain and snow events cause serious economic losses (Wang Lin et al., 2008; Wu Bingjuan et al., 2008; Zhou Shuxue, 2008; Yao Rong et al., 2012). The occurrence of freezing rain and snow events need both cooling and sufficient water vapor are satisfied. Moisture is the major control on weather conditions in north China, whereas southern China is controlled by temperature. Correspondingly, researchers have mainly focused on cold wave processes in north China and on freezing rain and snow events in south China (Qian Xi et al., 2013). In south China, persistent freezing rain and snow events generally have the characteristics of strong cooling and precipitation processes with a long duration. The occurrence of such events requires conditions such as high cold air activity and water vapor, which have a long period maintain or oscillation (He Jinhai and Sun Xiaojuan, 2017; Liao Chuan, 2017).

Some scholars have studied the possible precursor signals of typical freezing rain and snow weather cases. For example, deepening of the south trough and maintenance of the subtropical high were closely related to a freezing weather event in January 2008, and were caused by the downstream propagating Rossby wave energy along the subtropical jet from the northeast Atlantic Ocean and western Europe (Buhe Chaolu et al., 2008; Shi Ning et al., 2008; Ji Liren et al., 2008). Zhang Chunyan and Zhang Yaocun (2013) found that about half a month before events, the full wind speed up and zonal components of subtropical jet to enhance and the weaken polar peak jet began to show clear precursors. Bo Sun et al. (2018) showed that cold air activity was related to the decrease of early sea ice in the Arctic (Kara Sea and Barents Sea) during the snowfall process in East China in January 2018, while water vapor transport in the south was significantly related to the Northwest Pacific Ocean (La Nina) and the Atlantic Ocean; however, the mechanism of the influence of the Atlantic Ocean air-sea interaction on the snowfall process was unclear. Some scholars have also discussed the precursor signals of several combinations of frozen rain and snow weather. For example, Wang Lin et al. (2011) studied 19 years of strong snow and ice disasters in the Southern China and pointed out that the Antarctic Oscillation affected the sea surface temperature (SST) in the southern Indian Ocean two months in advance, and the SST increased abnormally, resulting in the occurrence of snow and ice disasters in the next year. Jiang Man et al. (2014) examined the period 1960–2008 and observed 23 periods of low temperature

sleet freezing events in south China's global reanalysis atmospheric variables data based on the physical decomposition of synoptic-scale disturbance component. Based on early signal analysis of the identified low temperature sleet freezing events, they found that before the incident, the 300-hPa height had the biggest negative disturbance; however, there was also a negative temperature perturbation at 850-hPa. Wang Li et al. (2016) studied the relationship between persistent low-temperature rain-snow weather and synoptic scale transient disturbance in southern China based on comparative analysis of four typical low-temperature rain-snow years and high-temperature rain-snow years in January. They showed that strong synoptic scale transient disturbance over the Atlantic Ocean propagated downstream in a wave pattern over the Eurasian continent. The eastward dispersion of the fluctuating energy provides a steady stream of energy for the activities of the trough ridge downstream, which is beneficial to the maintenance of atmospheric baroclinic instability and continuous low-temperature rain-snow weather in the southern region of China. In summary, the existing studies on the precursory signals of freezing rain and snow events are mostly qualitative studies for a few cases, and possible signals indicating the occurrence of the event have been proposed, including the atmospheric signals in the upstream and upper air during the freezing rain and snow mid-term process, as well as the signals of out-of-season SST and out-of-sea ice forcing.

The 10–30-day extended-period forecast is the “forecast gap” between the conventional weather forecast and the short-term climate forecast, which plays an important role in the development of meteorological business and national economic services. It is not only a major research topic, but also an important development direction of the current forecast decision-making services (He Jinhai et al., 2013). Studies have shown that the atmospheric slow process in this period is the most predictable, and thus a large number of studies have focused on the extraction and prediction of these low-frequency variation signals. Nevertheless, there are still many precursor signals that have not been extracted (Jin Ronghua et al., 2010). Sun Xiaojuan et al. (2021) divided the persistent freezing rain and snow events in the history of South China into three categories, among which the events in Southwest China occurred at high frequency, had long duration and strong intensity. Therefore, this study aimed to systematically examine the causes of persistent freezing rain and snow events in southwest China and identify atmospheric signals in the extended-period before the events by using the atmospheric remote correlation theory. This understanding could be applied to

greatly improve the prediction ability of the extended period relating to freezing rain and snow events in southern China.

2. methods

a. Freezing index

Station freezing days in southern China were defined as station daily mean temperature less than 1.0°C with the presence of precipitation. If the freezing days continue three days at least, the period is identified as a persistent freezing rain and snow weather event (Wang Haijun, 2008; Wang Lin, 2011). For each freezing rain and snow event, the freezing index Z can be calculated using the following equations:

$$I_{ij,1} = \frac{d_{ij} - d_{\min}}{d_{\max} - d_{\min}} \quad (1)$$

$$I_{ij,2} = \frac{r_{ij} - r_{\min}}{r_{\max} - r_{\min}} \quad (2)$$

$$I_{ij,3} = -\frac{\bar{t}_{ij} - \bar{t}_{\min}}{\bar{t}_{\max} - \bar{t}_{\min}} \quad (3)$$

$$I_{ij,4} = -\frac{tl_{ij} - tl_{\min}}{tl_{\max} - tl_{\min}} \quad (4)$$

$$Z_{ij} = \frac{I_{ij,1}}{I_1} + \frac{I_{ij,2}}{I_2} + \frac{I_{ij,3}}{I_3} + \frac{I_{ij,4}}{I_4} \quad (5)$$

where d is the duration of the weather conditions in days; i is the sequence number of stations; j is the sequence number of freezing rain and snow events; $d_{\max}$ and $d_{\min}$ are the maximum and minimum weather duration of the weather conditions in days for all events, respectively; r is the total precipitation during the event; and $r_{\max}$ and $r_{\min}$ are the maximum and minimum total precipitation across all events, respectively; $\bar{t}$ is the average temperature of the event; $\bar{t}_{\max}$ and $\bar{t}_{\min}$ are the highest and lowest average temperature across all events, respectively; tl is the minimum temperature of the event; and $tl_{\max}$ and $tl_{\min}$ are the highest and lowest event minimum temperatures across all events, respectively.

$I_{ij,1}$, $I_{ij,2}$, $I_{ij,3}$, $I_{ij,4}$, are the average values of four factors, include freezing persistent days, total precipitation, average temperature and minimum temperature, respectively. Z_{ij} is the comprehensive freezing weather process index in South China (abbreviated as freezing

index). Using Z_{ij} to calculate the annual average can obtain an annual series of freezing index, as Z .

In this paper, this method was used to calculate the winter freezing index in southwest China (100°E – 110°E , 22.5°N – 32.5°N) and obtain the southwest China regional average annual series, Z_{sw} , which was used to characterize the intensity of freezing rain and snow events in southwest China in winter during 1951–2017. In addition, the strong years and processes of freezing rain and snow events were screened (Table 1), where start date was defined as the first date in which at least 20% of stations in southwest China suffer from freezing rain and snow events and the end date is the day before the number of freezing stations in the southwest region decreases to less than 20% during an event. The outbreak date is a day in which the total number of freezing affected stations reaches the peak. The 13 strong freezing rain and snow events in southwest China generally lasted for an average of about 17.5 days, and most of the events occurred in January and February of the following year after December. On the outbreak day of the event, the precipitation in southern China was exceptionally high (FIG 1).

Start	End	Outbreak	Duration (days)	Freezing index
1954-12-23	1955-01-06	1954-12-28	15	25
1956-01-18	1956-02-04	1956-01-30	16	24
1957-02-08	1957-02-28	1957-02-20	21	32
1958-02-03	1958-02-21	1958-02-05	19	31
1959-02-14	1959-02-28	1959-02-16	15	25
1968-01-29	1968-02-13	1968-02-05	16	24
1972-02-01	1972-02-10	1972-02-03	10	24
1982-02-03	1982-02-16	1982-02-05	14	23
1984-01-15	1984-02-12	1984-01-16	29	44
1995-02-13	1995-02-28	1995-02-19	16	21
2000-01-24	2000-02-05	2000-01-28	13	20

2000-02-19	2000-02-29	2000-02-25	11	21
2008-01-12	2008-02-14	2008-01-13	33	59

Table 1 Strong persistent freezing rain and snow events in southwest China in winters of 1951–2017.

Fig. 1. Anomalous precipitation in southwest China indicating strong persistent freezing rain and snow events.

b. Station PT index

Station PT index (precipitation and temperature index) (Zhang, 2011) is the difference between precipitation and temperature after standardization, which emphasizes the equal importance of precipitation and temperature. It was determined as follows:

$$PT_i = \frac{P_i - \bar{P}}{p_s} - \frac{T_i - \bar{T}}{T_s} \quad (6)$$

where P_i and T_i are the average monthly precipitation and surface temperature in southern China, respectively; $\bar{P}$ and $\bar{T}$ are the average precipitation and temperature in the same period of history, respectively; and p_s and T_s are the standard deviations of precipitation and temperature in the same period of history, respectively. In this paper, the method was modified to:

$$PT_{ij} = \frac{P_{ij} - \bar{P}}{p_s} - \frac{T_{ij} - \bar{T}}{T_s} \quad (7)$$

where P_{ij} and T_{ij} are the daily precipitation and surface temperature at Station j on Day i , respectively; $\bar{P}$ and $\bar{T}$ are the average of precipitation and temperature in the same period

of history, respectively; and p_s and T_s are the standard deviation of precipitation and temperature in the same period of history, respectively. Here, PT_{ij} index is used in to represent the intensity of precipitation and temperature change during a freezing rain and snow event.

c. Mongolia high pressure circulation index

The Mongolian high pressure intensity index P , area index S and central position index (λ_c, φ_c) were calculated according to the universal definition method for a circulation index of closed pressure system proposed by Wang Panxing et al. (2007) and the set of Mongolian high pressure circulation indexes defined by Liu Qingqing et al. (2011). For the 1000 hPa isobaric surface in the number t year, for year t where t is 1951 to 2017, the three circulation indexes of the Mongolian high were identified as follows: (1) the area index $S(t)$ is the area of the region, which is surrounded by a computational field $D(t)$ in a sphere of unit radius search area Ω ; (2) intensity index $P(t)$ is defined as the surface integral of geopotential height difference $\Delta H(t) = H(t) - f_0$ in the $D(t)$; and (3) the center position index $(\lambda_c(t), \varphi_c(t))$ is the latitude and longitude of the gravity field center corresponding to $\Delta H(t)$ over the region $D(t)$. Liu Qingqing (2011) showed that the search area Ω used in the calculation of Mongolian high pressure is 60°E–130°E and 20°N–70°N. The characteristic contour (December–February) is $f_0 = 220$ gpm.

Fig. 2. Mongolian high pressure search area Ω and the winter characteristic contour
 $f_0 = 220\text{gpm}$ from 1951 to 2017

3. Definition of the key combined anomalies index

Studies have shown that the cooling process in southwest China in winter is significantly controlled by the Mongolian high-pressure activities (Sun Xiaojuan et al., 2010), while precipitation is closely related to the activities of the south branch trough (Qin Jian et al., 1991; Suo Miaoqing and Ding Yihui, 2009). The previous study (Ma Juhui et al., 2008) showed that during the persistent freezing rain and snow event in southwest China, the Mongolian high-pressure activity was abnormal, its intensity was strongly enhanced, and the location was more easterly and southward. The intensity of the south trough was significantly enhanced, which increased activity of the water vapor transport in the south. The variation trend of the intensity index of the south trough before and after the outbreak of the event is similar to that of the Mongolian high-pressure intensity index. The average Mongolian high strength index, north-south position index, and south trough strength index during events were determined for the 13 strong persistent freezing rain and snow events in southwest China screened above. The results show that the southern trough activity was significantly stronger than the climate state during 12 of the 13 events. In 7 of the 13 events, the Mongolian high-pressure intensity was stronger (Fig. 3a), and in 6 of the 13 events, the Mongolian high-pressure intensity was slightly weaker than the climate state. However, during these events, the position index of the Mongolian high was more southward than the climatic average because the abnormal southward oscillation of the Mongolian high is also conducive to the southward transport of cold air (Fig. 3b). Ma Juhui et al. (2008) studied the characteristics of high-pressure activity in Mongolia during the occurrence of low temperature freezing injury in southern China in early 2008 and showed similar conclusions.

Fig. 3. Thirteen Southwest China strong persistent freezing rain and snow events, (a) Mongolia high pressure (MHO) intensity and south branch trough (SBT) intensity index; (b) Mongolia high pressure (MHO) intensity and north-south position (Sita) index.

Based on the Mongolian high pressure intensity index in winter, the latitude index of the Mongolian high and the intensity index of the southern branch trough to return to the annual freezing index (Equation 3.1), the combination index of annual anomalies of the Mongolian high and the southern branch trough in winter were established. The index obtained after regression has a good fit with the freezing index, with a correlation coefficient of 0.720 (Fig. 4a). The anomaly combination index of Mongolia high pressure and south branch trough (hereinafter referred to as the key combined anomalies index P_{CA}) is as follows:

$$P_{CA} = 0.48\tilde{P}_{MHO} + 0.16\tilde{P}_{Sita} + 0.61\tilde{P}_{SBT} \quad (8)$$

where P_{MHO} is the Mongolia High Pressure Intensity Index, the surface integral of geopotential height difference $\Delta H(t) = H(t) - f_0$ in the $D(t)$, which is in the unit radius of sphere search area Ω . The north-south position index of Mongolian high P_{Sita} is the latitude and longitude of gravity field center corresponding to $\Delta H(t)$ over the region $D(t)$. South branch index P_{SBT} is the average geopotential height from northern Bay of Bengal to southern Qinghai-Tibetan Plateau at 700 hPa (Suo Miaoqing, Ding Yihui, 2009). To facilitate the expression, the latitude index P_{Sita} and the index P_{SBT} of the Mongolian high are negative of the original index. The larger the value of P_{Sita} , the more southward the Mongolian high, and the larger the value of P_{SBT} , the stronger the southern trough.

Among the 13 strong persistent freezing rain and snow events in southwest China, the average key combined anomalies index of 12 of the 13 events was stronger than the climate state (Fig. 4b). The index characteristics of key combination anomaly synthesized on a daily basis showed that the index significantly increased 6 days after the outbreak of the leading event, reached the peak one day after the outbreak of the event, and was then maintained at a high level for more than 10 days. This is consistent with the occurrence and maintenance time variation characteristics of strong persistent frozen rain and snow events (Fig. 4c).

Fig. 4. (a) Southwest China winter freezing index and the combined anomalies index during 1951–2017, (b) the anomaly of the combined anomalies index of the 13 strong persistent freezing rain and snow events in southwest China, and (c) the average of the combined anomalies index during the 13 events.

To further verify the characterization ability of the key combined anomalies index established above on the cooling and precipitation process in southwest China, the daily key combined anomalies index and the average daily PT index in southwest China were used to calculate the correlation coefficient (Table 2). A positive correlation was observed between

the daily key combined anomalies index and the daily mean PT index during the strong persistent freezing rain and snow events in southwest China, of which 9 of the 13 events were significantly positively correlated.

Therefore, the key combined anomalies index, established by the Mongolian high pressure intensity index, Mongolian high latitude index and southern trough intensity index, can better characterize the cooling and precipitation process in southwest China during the strong persistent freezing rain and snow events. A significant increase in the key combined anomalies index in the same period indicates that the Mongolian high is stronger in intensity and more southerly in location, and the southern trough is more active. In this case, it is more likely that strong persistent freezing rain and snow weather will occur in southwest China. When the index is weak, the southwest of China has high temperature and less precipitation, and persistent freezing rain and snow weather are less likely.

Lag Year	lag 6 days	lag 5 days	lag 4 days	lag 3 days	lag 2 days	lag 1 day	lag 0 day
1954	0.467*	0.572*	0.705*	0.757*	0.728*	0.613*	0.473*
1955	-0.025	0.142	0.220	0.334*	0.649*	0.831*	0.715*
1956	0.125	0.440*	0.510*	0.286	0.000	0.237	0.612*
1957	-0.350	-0.070	-0.039	0.131	0.259	0.449*	0.775*
1958	0.095	-0.305	0.016	0.043	0.156	0.350	0.443*
1967	0.170	0.383	0.306	0.367	0.315	0.172	0.188
1971	-0.294	-0.293	0.063	0.481	0.367	-0.040	0.131
1981	-0.393	-0.055	0.392	0.221	-0.226	0.071	0.682*
1983	-0.366	-0.293	-0.126	0.036	0.030	0.106	0.355*

1994	-0.116	-0.094	-0.011	0.078	0.013	0.140	0.285
1999	0.003	0.097	0.149	0.033	0.325	0.691*	0.719*
1999	0.418	0.451	0.529	0.585*	0.414	0.196	-0.034
2007	0.332*	0.328*	0.269	0.226	0.307*	0.424*	0.455*

Table 2 Time lag correlation coefficient between combined anomaly index and PT index in southwest China. *Signifies passing the significance test of $\alpha = 0.1$.

The above discussion reveals that the key combined anomalies index P_{CA} can be established by using the multiple linear regression method and Mongolia high intensity index, latitude index and south branch trough intensity index. The Pearson correlation method was used to examine the characteristics of key anomaly combination index P_{CA} for the cooling and precipitation process in southwest China. It was found that the P_{CA} of the same period three solstices ahead had a good positive correlation with the PT index in south China, and thus when P_{CA} increases (decreases), the Mongolian high is stronger (weaker) and positioned more southward (northward) and the southern trough is stronger (weaker), which is conducive to the cooling (warming) and increasing (weakening) of precipitation in southwest China. In conclusion, the key combined anomalies index P_{CA} can be used as a link to explore the precursor signals of persistent freezing rain and snow events in southwest China and lay a foundation for improving the ability of intra-season and short-term climate prediction of events.

4. Analysis of the forecast signal of strong persistent freezing rain and snow events in southwest China

a. Relationship between height field and key anomaly combinations in upstream areas within seasons

Among the 13 strong persistent freezing rain and snow events in southwest China screened above, the key combined anomalies index of 9 events had a good ability to characterize the cooling precipitation in southwest China in the same period. Therefore, the correlation between the key combined anomalies index of these nine events and the previous

height field was used to explore the intra-seasonal signals of strong persistent freezing rain and snow events in southwest China.

Fig. 5 shows the time-delay correlation between the exponent and the 1000-hPa height field. The low geopotential height of Iceland in the leading index from 15–20 days showed a significant negative correlation with the index during the same period, whereas the middle and low latitudes of the North Atlantic showed a significant positive correlation center (Fig. 5a, b). In addition, there was a significant positive correlation in the Black and Caspian Sea region, which gradually strengthened over time (Fig. 5b). On the 10th day of the lead index, the negative correlation area in the west of Iceland at high latitude moved eastward to the sea to the east of Iceland, the positive correlation center in the North Atlantic at middle latitude moved to Western Europe, and the positive correlation center in the Caspian Sea moved northeast (Fig. 5c). During the following 5 days, the negative correlation between the North Atlantic and Europe in high latitude decreased, and the Asian continent showed a significant high positive correlation over a large range (Fig. 5d). In the same period, the index was significantly positively correlated with the 1000-hPa Mongolian high and negatively correlated with the geopotential height of the East Asian subtropical region (Fig. 5e). In addition, the time-delay correlation between the height fields of 500-hPa, 200-hPa and the key anomaly combination index was calculated, and the results are similar to those for 1000-hPa.

Therefore, a low 1000-hPa geopotential height of Iceland in the upper reaches of the Eurasian continent may lead to a larger key anomaly combination index in the lower reaches of the Eurasian continent in the later stage. A high 1000-hPa geopotential height of the mid-latitude North Atlantic, Europe and the Caspian Sea in the upper upstream in the early stage may also increase the key anomaly combination index of lower Eurasia in the later stage (Fig. 6).

Fig. 5. The delay-dependent between the 1000-hPa height field and the combined anomalies index for a lag of (a) 20 days, (b) 15 days, (c) 10 days, (d) 5 days and (e) 0 days.

Fig. 6 The relationship between the combined anomalies index and the anomaly of the average geopotential height in the upstream key area, and its linear regression during nine southwest China strong persistent freezing rain and snow events based on (a) the Iceland area (60°N–80°N, 10°W–50°W), (b) the mid-latitude Atlantic (25°N–45°N, 20°W–60°W) and (c) the Caspian sea region (30°N–50°N, 30°E–70°E).

b. Influence mechanism of intra-seasonal precursory signal on freezing rain and snow events

The key regions of the upper North Atlantic and Europe geopotential height that determined by the time-delay correlation method may be related to the key anomaly combination index. Therefore, the surface geopotential height near Iceland was reduced, 15–20 days ahead of the upstream, and the surface geopotential height over the North Atlantic in mid-latitude and Europe to the Caspian Sea was higher. This caused the downstream Mongolian high to strengthen and move southward, as well as the deepening of the south branch trough. To further study the physical mechanism of the height correlation between the upstream and downstream ground potential, the height disturbance and T-N wave flux are shown in Fig. 7.

Twenty days before the outbreak of the event, there was a strong negative height disturbance near Iceland in the upper troposphere, and a positive height disturbance in the mid-latitude North Atlantic (Fig. 7a). The polar vortex in the polar region was strengthened in the upper air from North America to the North Atlantic, and abnormal high pressure developed along the North American coast in the mid-latitude Atlantic. After the circulation shaped development trough, the northwest airflow guided the transport and accumulation of cold air from the high latitude area of North America to the mid-latitude North Atlantic, creating a positive anomaly at the geopotential height of the whole layer in this region 20 days or so before the outbreak of the leading event (Fig. 8b). In addition, because of the significant enhancement of the polar vortex, the disturbance energy from the negative geopotential height from Greenland to Iceland was transmitted down to the ground in the earlier stage (Fig. 8a). At the same time, the clear positive geopotential height disturbance over Europe (Fig. 7a, b) indicates that the development of the high-pressure ridge in this region increases the transport of cold air from the Barents Sea to Southeast and Eastern Europe. Like the development of geopotential height over the North Atlantic, the surface cold air mass accumulates over the Black Sea and the Caspian Sea (Fig. 8c). Then, 5-10 days before the events, the North Atlantic long wave train developed downstream, and the negative geopotential height disturbance center moved eastward over Europe, and the positive geopotential height disturbance center moved to the Ural Mountains area (Fig. 7c, d). Long wave disturbance energy along the north and south two downstream expedited axial dispersion, the northern branch wave train later developed between the Ural Mountains and Lake Baikal ridge, thus strengthening the Mongolian high (Fig. 7e). The increase of high-level meridional circulation in east Asia guided polar cold air from the Siberia key area near the Barents sea, where it accumulated, causing the east Asian trough to deepen. The south

branch wave train to the downstream of the dispersion of wave energy deepened the late southern trough over the Arabian peninsula and the bay of Bengal, and the early stage of the upper latitude (Iceland) negative geopotential height caused disturbance along the path from Europe through the Caspian sea and the Arabian peninsula to India. The disturbance moved downstream through the low latitudes, eventually leading to the negative geopotential height anomaly in the southern trough area on the event day.

Most of the strong persistent freezing rain and snow events in southwest China were anomalously strong from North America to the North Atlantic polar vortex at high latitudes in the upstream areas 15–20 days before the events occurred, and ridges developed over the west Atlantic Ocean at mid-latitude and over Europe. Under the influence of these disturbances, the geopotential height near Iceland decreased at 1000-hPa, and the geopotential height in the North Atlantic and the Black Sea and Caspian Sea increased at mid-latitude. The geopotential height response at the surface was significantly correlated with the key anomaly combination index established by the south branch of the Mongolian high downstream. Overall, the high field disturbance signal in the upstream areas enhanced the high pressure in the downstream parts of Mongolia and deepened the south trough through the interaction of wave and current, finally resulting in the strong persistent freezing rain and snow events in southwest China.

Fig. 7. 300-hPa geopotential height (contour, unit: gpm), geopotential height anomaly (colored, unit: $10^6 \text{ m}^2/\text{s}^2$) and T-N wave flux (vector, unit: m^2/s^2) during strong persistent freezing rain and snow events in southwest China for a lag of (a) 20 days, (b) 15 days, (c) 10 days, (d) 5 days and (e) 0 days.

378

379 Fig. 8. Upstream critical area average geopotential height disturbance height-time profile
 380 during southwest China strong persistent freezing rain and snow events based on (a) the
 381 Iceland area, (b) the mid-latitude Atlantic and (c) the Caspian Sea region.

382 *c. Definition of the intra-seasonal forecast index*

383 Based on the key anomaly combination index of nine strong persistent freezing rain and
 384 snow events in southwest China and the height anomaly of three key upstream regions
 385 (Iceland, the North Atlantic and the Caspian Sea) 15 days ahead and the regression results,
 386 the following equation was obtained:

$$387 \quad I_f = -0.37\widetilde{H}_{IL} + 0.22\widetilde{H}_{NA} + 0.31\widetilde{H}_{CS} \quad (8)$$

388 where $\widetilde{H}_{IL}$, $\widetilde{H}_{NA}$ and $\widetilde{H}_{CS}$ are respectively three normalized height anomaly
 389 sequences in the key region (Iceland, the North Atlantic and the Caspian Sea) of upstream
 390 early signals, and I_f is the Intra-seasonal forecast index. The fitting degree of the regression
 391 equation is high, and the correlation coefficient passes the significance test of $\alpha = 0.01$ (Fig.
 392 9). The results show that, except for the winter events in 1981 and 2007, the PT index in
 393 southwest China is positively correlated with the intra-seasonal prediction index established
 394 by the high disturbance in the upstream key areas 16 days or later during seven of the nine
 395 strong persistent freezing rain and snow events in southwest China, of which five of the nine
 396 events are significant (Table 3). This indicates that the new index derived in this paper can be

used to predict most of the strong persistent freezing rain and snow events in southwest China caused by the combination of the Mongolian high and the south trough anomaly. However, for some persistent freezing rain and snow events (winter 1981 and winter 2007), the new index has a weak ability to predict, which may be because there are other key factors besides the Mongolian high and south trough, for example, some studies have shown that the 2007 event subtropical high also showed abnormal activities, but this is not considered specifically in the current research and thus needs to be further studied.

Fig. 9. The combined anomalies index and extended intra-seasonal prediction index at a lag of 16 days. Red dotted lines separate the nine events

Lag Year	-20	-19	-18	-17	-16	-15
1954	-0.312	0.156	0.582*	0.722*	0.558*	0.328
1955	0.442*	0.624*	0.682*	0.654*	0.556*	0.333*
1956	0.229	0.014	-0.029	-0.009	0.026	0.241
1957	0.181	-0.212	-0.499	-0.384	0.475	0.667*
1958	0.353*	0.486*	0.432*	0.395*	0.409*	0.379*
1981	0.135	-0.046	-0.378	-0.436	-0.434	-0.532
1983	-0.474	-0.147	0.284	0.240	-0.081	-0.252
1999	0.257	0.289	0.384	0.474	0.541*	0.407
2007	-0.174	-0.121	-0.102	-0.162	-0.215	-0.160

Table 3 Correlation coefficient between intra-seasonal prediction index and PT index in southwest China. *Signifies passing the significance test of $\alpha = 0.1$.

d. summary

During the 15–20 days prior to the event (1000 hPa), the height fields of the North Atlantic, Iceland and the Caspian Sea in the middle latitudes showed significant positive, negative and positive correlations with the key anomaly combination indexes, respectively. The phase of the wave train in the upstream region continued to propagate to the downstream region before the event occurred, while its wave energy kept dispersing to the downstream, causing the Ural high pressure ridge in the downstream region to develop and be maintained into the later period. On the ground, the enhancement of the Mongolian high pressure and the deepening and maintenance of the south branch trough occurred (Fig. 9), eventually leading to a persistent freezing rain and snow event in southwest China. Based on multiple linear regression and the height anomaly of the key anomaly combination index of strong persistent freezing rain and snow events in southwest China and the three key regions (Iceland, the North Atlantic and the Caspian Sea) 16 days ahead of the key anomaly combination index, the intra-season prediction index I_f was calculated. At around 15 days in advance, I_f is significantly correlated with the PT index of the most persistent freezing rain and snow events in southwest China, indicating that the precipitation cooling process can be characterized by the key anomaly combination index. Therefore, I_f is able to predict Mongolian high southern trough combination anomalies caused by continuous freezing rain and snow events in southwest China.

5. Discussion

In this study, we screened 13 strong freezing rain and snow events (100°E–110°E, 22.5°N–32.5°N) in the southwest region of southern China during the winter of 1951–2017 and explored the seasonal precursor signals for these events. The main conclusions are as follows: (1) it is possible to build a key anomaly combination index using the Mongolian high strength index, location index and the southern trough intensity index. At 3 to 0 days in advance, the key anomaly combination index and the southern China PT index showed a good positive correlation, and the key anomaly combination index can be used as a precursor to explore the sustainability of the freezing rain and snow events in the southwest signal. (2) On the surface of the North Atlantic, Iceland and Caspian Sea at mid-latitude (1000 hPa)

during the 15–20 days prior to the event, the height fields of the three key regions showed significant positive, negative and positive correlations with the key anomaly combination indexes, respectively. At 15–20 days before the occurrence of most of the southwest type of strong persistent freezing rain and snow events, the upstream high latitude North America to North Atlantic polar vortex was abnormally strong, and the mid-latitude west Atlantic Ocean and Europe, respectively, showed ridge development. Under the influence of this disturbance, the geopotential height near Iceland decreased at 1000 hPa, and the geopotential height in the North Atlantic and the Black Sea and the Caspian Sea increased at mid-latitude. The geopotential height response at the surface was significantly correlated with the key anomaly combination index established by the south branch of the Mongolian high downstream. The high disturbance signal in the upstream enhanced the Mongolian high pressure and deepened the southern trough in the downstream through the wave–current interaction, finally resulting in the strong persistent freezing rain and snow event in the southwest. (3) Using the multiple linear regression method, the intra-season forecast index I_f can be established according to the average geopotential height of key regions and the combination index of key anomalies 16 days ahead of the event. There was a negative correlation between I_f index and the average PT index of southwest China, which could have important applications in seasonal forecasting.

In this paper, the key anomaly combination index was established by using the significant anomaly influencing system (Mongolia high, southern trough) in the occurrence of persistent freezing rain and snow events in southwest China, which was used as the link to explore the precursor signals of persistent freezing rain and snow events. However, this research did not consider whether the index is universal to the persistent freezing rain and snow events in other regions of China. Therefore, to systematically discuss the precursor signals of persistent freezing rain and snow events in southern China, it is necessary to further verify the ability of the index to represent the cooling and precipitation process of persistent freezing rain and snow events in other parts of southern China. It was also found in this study that not all the key abnormal combination indices of strong persistent freezing rain and snow processes in southwest China can accurately represent the cooling and precipitation processes, which may be related to the significant influence of other circulation systems on such events. In addition, the assessment of precursor signals was limited to the medium-term process signals 10–20 days ahead of the event. Many studies have shown that the abnormal signal of temperature and precipitation in winter in China can be traced back to abnormal

external forcing factors such as SST and sea ice in the previous spring, summer and autumn, and thus future research is needed to further improve understanding of the precursor signals of persistent freezing rain and snow events in southwest China.

Acknowledgments.

This work was supported by the National Key Research and Development Program of China(Grant No. 2018YFC1505602), the National Natural Science Foundation of China (Grant No. 41705055, 41505088), the Project of Scientific Creation of Post-Graduates of Jiangsu (Grant No. CXZZ12_0485), the Creative Teams of Jiangsu Qinglan Project and the Priority Academic Program Development of Jiangsu Higher Education Institutions(PAPD). I am grateful for the very constructive comments of two reviewers.

Data Availability Statement.

The data examined in this research were daily temperature and precipitation taken from 753 stations across China, provided by China National Meteorological Information Center from 1950 to 2018 (<http://data.cma.cn>). In addition, monthly and daily NECP/NCAR reanalysis data were examined with a mesh accuracy of $2.5^{\circ} \times 2.5^{\circ}$ and vertical levels in the range 1000–300 hPa. The examined variables were horizontal wind, vertical wind speed, geopotential height, temperature, relative humidity and absolute humidity (<https://www.esrl.noaa.gov>).

REFERENCES

- Bo Sun , Wang Huijun, Botao Zhou .Climatic Condition and Synoptic Regimes of Two Intense Snowfall Events in Eastern China and Implications for Climate Variability[J]. Journal of Geophysical Research: Atmospheres, 2019, 124(2).
- Cholaw B , Li-Ren J I . On the Medium-Range Process of the Rainy,Snowy and Cold Weather of South China in Early 2008 Part I:Low-Frequency Waves Embedded in the Asian-African Subtropical Jet[J]. Climatic and Environmental Research, 2008, 13(4):419-433.

501 DING Yihui, WANG Zunya, SONG Yafang, et al. Causes of the rare low temperature rain
502 and snow freezing disaster in January 2008 in southern China and its relationship with
503 climate warming [C]// CNKI. CNKI, 2008:158-175.

504 Du Xiaoling, Gao Shouting, Peng Fang. Study on the Cause of Continuous Low Temperature
505 Rain and Snow Freezing Weather in Guizhou in Early 2011 [J]. Chinese Journal of
506 Atmospheric Sciences, 2014, 38(001):61-72.

507 GAO Hui, CHEN Lijuan, JIA Xiaolong, et al.. Analysis of large-scale low-temperature rain
508 and snow freezing disaster in China in January 2008 II. Analysis of cause [J]. Weather,
509 2008 (4) : 101-106.

510 Gu Lei, Wei Ke, Huang Ronghui. Relationship between Severe Low Temperature Freezing
511 Disaster and East Asian Monsoon System Anomalies in January 2008 in China [J].
512 Climatic and Environmental Research, 2008, 13(004):405-418.

513 He Jinhai, Sun Xiaojuan. The 34th annual meeting of the Chinese Meteorological Society. 0.

514 JIA Xiaolong, ZHAO Zhenguo, LI Weixing, et al. Journal of Applied Meteorology, 2013,
515 24(006):641-655. (in Chinese with English abstract)

516 Jiang Man, Yu Tiantian, Qian Weihong. Chinese Journal of Atmospheric Sciences, 2014,
517 38(004):813-824. (in Chinese)

518 LI Chongyin, YANG Hui, GU Wei. Climatic and Environmental Research, 2008(02):113-
519 122. (in Chinese)

520 Li-Ren J I , Cholaw B , Shi N . On the Medium-Range Process of the Rainy,Snowy and
521 Cold Weather of South China in Early 2008 Part III:Pressure Trough over the Tibetan
522 Plateau/Bay of Bengal[J]. Climatic and Environmental Research, 2008.

523 LI Weixing, ZHENG Zhihai, SUN Chenghu. Advances in the research and application of
524 dynamic similarity prediction methods in short-term climate prediction in China in recent
525 years [J]. Chinese Journal of Atmospheric Sciences, 2013, 37(002):341-350.

526 LI Yan, WANG Shigong, JIN Ronghua, et al. Analysis of anomalous characteristics of
527 blocking high during freezing rain and snow disaster in southern China. PLATEAU
528 METEOROLOGY, 2012, 31(1):94-101.

529 Liao curriculum. Circulation Typing Characteristics of Persistence Low Temperature Rain
530 and Snow Freezing Events in South China [D]. Chinese Academy of Meteorological
531 Sciences.

532 LIU Qingqing, WANG Panxing, XU Xiangde, et al. Journal of Tropical Meteorology, 2011,
533 27(6):889-898. (in Chinese with English abstract)

534 Liu X M, Gao A N, Zhao J B. Characteristics and causes of freezing disasters of low
535 temperature rain and snow in western South China in 2011 [J]. Journal of Natural
536 Disasters, 2013, 22(06):232-239.

537 Ma J H, Wang P X, Li L P, et al. The relationship between "snow disaster in South China
538 0801" and medium-term high-pressure activity in the same period in Mongolia [J].
539 Chinese Journal of Atmospheric Sciences, 2010, 32(5):652-660.

540 QIAN Xi, ZHAI Panmao. Analysis of low temperature rain, snow and freezing events and
541 their variation characteristics in mainland China [C]// Innovation-driven development to
542 improve meteorological disaster prevention ability -- S2 disaster weather monitoring,
543 analysis and forecast. 2013.

544 QIAN X. Low temperature rain and snow events in central and eastern China in January 2018
545 and their comparative analysis with 2008 [C]// The 35th Annual Meeting of Chinese
546 Meteorological Society S1 Disaster Weather Monitoring, Analysis and Forecast, 2018. (in
547 Chinese with English abstract)

548 Qian J L , 2 1 Department of Atmospheric Sciences, Physics S O , et al. Frontal genesis of
549 moisture atmosphere during the early 2008 persistent freezing-rain event in southern
550 China[J]. Science China(Earth Sciences), 2010.

551 Qin Jian, Pan Linna. Effect of combination of south branch trough and strong cold air on
552 winter weather in yunnan. METEOROLOGY, 1991, 17(003):39-43.

553 Shi N, Bu H C L, Ji L R, et al. Analysis of the mid-term process of rain and snow low
554 temperature weather in South China in early 2008 II: Characteristics of the western
555 Pacific subtropical high [J]. Climatic and Environmental Research, 2008(04):434-445.

556 Shiyan T , WEI Jie. Severe Snow and Freezing-Rain in January 2008 in the Southern
557 China[J]. Climatic and Environmental Research, 2008.

558 SUN Xiaojuan, Li Siyan, YU Yueyue, et al. Climatic characteristics of persistent frozen rain
559 and snow events in southern China during the winter 1951-2017 and their relationship
560 with the combinational anomaly of circulation [J]. Chinese Journal of Atmospheric
561 Sciences, to be published.

562 SUN Xiaojuan, WANG Panxing, ZHI Hai, et al. Analysis and comparison of several
563 circulation indexes of Mongolian high and its correlation with winter temperature
564 anomaly in China [J]. Plateau Meteorology, 2010, 029(006):1493-1500.

565 Suo Miaqing, Ding Yihui. Structure and evolution of the westerly trough in the southern
566 branch of the subtropical zone in winter half year. Chinese Journal of Atmospheric
567 Sciences, 2009, 033(003):425-442.

568 WANG Li, GAO Jie, ZENG Bo. Spatio-temporal distribution and causes of low temperature
569 rain and snow events in southern China [J]. Plateau and Mountain Meteorology Research,
570 2016(36):39-43. (in Chinese)

571 Wang Haijun, Qin Jun, Zhang Jun. Resources and Environment in the Yangtze Basin, 2010,
572 19(7):839.

573 WANG Lin, QIN Jun, CHEN Zhenghong, et al. Statistical analysis of circulation and
574 anomaly of meteorological elements in freezing rain and snow disaster years in South
575 China [J]. Resources and Environment in the Yangtze Basin, 2011(S1):173-180.

576 Wang Lin. Analysis of Atmospheric Circulation Anomaly in Snow and Ice Disaster Weather
577 in South China [D]. China University of Geosciences (Wuhan).

578 Wang L, Gao G, Zhang Q, et al. Analysis of large-scale cold rain and snow freezing disaster
579 in China in January 2008 I. Climate characteristics and impact assessment. The weather.

580 WANG Panxing, LU Chuhan, GUAN Zhaoyong, et al. Journal of Nanjing Institute of
581 Meteorology, 2007, 30(6):730-735. (in Chinese)

582 WANG, Yi, YAN, et al. Trends in Seasonal Precipitation over China during 1961-2007[J].
583 Atmospheric and Oceanic Science Letters, 2009, 2(3):165-171.

584 Wang D , Liu C , Liu Y , et al. A Preliminary Analysis of Features and Causes of the
585 Snow Storm Event over the Southern Areas of China in January 2008[J]. Journal of
586 Meteorological Research, 2009, 23(3):374-386.

587 XIONG, Zhe, XIONG, et al. Simulation of a Freezing Rain and Snow Storm Event over
588 Southern China in January 2008 Using RIEMS 2.0[J]. Atmospheric & Oceanic Science
589 Letters, 2013.

590 YAO Rong, XU Lin, ZHANG Hai, et al. Comparative Analysis of Causes and Effects of Two
591 Low Temperature Rain and Snow Freezing Disasters in Hunan Province in 2008/2011 [J].
592 Journal of Catastrophology, 2012(04):75-79.

593 Zhang C Y, Zhang Y C. Characteristics of the upper-level jet stream over East Asia during
594 the continuous low-temperature rain-snow freezing event in early 2008 [J]. Journal of
595 Tropical Meteorology, 2013(02):306-314.

596 Zhang H , Qin J , Yun L . Climatic background of cold and wet winter in southern China:
597 part I observational analysis[J]. Climate Dynamics, 2011, 37(11-12):2335-2354.

598