Variation Characteristics of Cold Waves in Ningxia over the Past 60 Years and the Imprint of Circulation Anomalies

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Abstract

Using daily minimum temperature observation data in Ningxia from 1961 to 2020 and monthly reanalysis data of geopotential height, sea level pressure field, and wind field during the same period, this study analyzes the spatiotemporal evolution characteristics of cold waves, strong cold waves, and extreme cold waves with different durations (24 h, 48 h, and 72 h) in Ningxia over the past 60 years, and further reveals the atmospheric circulation anomaly characteristics of cold wave variations. The results show that: (1) Over the past 60 years, cold waves of different intensities and durations in Ningxia have consistently exhibited a distribution pattern of "more in the east and less in the west, more in the north and less in the south," which is related to the cold air paths and the topography of Ningxia. (2) The frequencies of cold waves, strong cold waves, and extreme cold waves in the entire region account for 71.7%, 22.6%, and 5.7% of the total annual cold wave frequency, respectively. Cold waves are dominated by 24 h and 48 h durations, while the frequency proportions of different durations are relatively comparable for strong and extreme cold waves. All types of cold waves exhibit a monthly variation pattern of decreasing from January to April and increasing from October to December. (3) Over the past 60 years in Ningxia, cold waves, strong cold waves, and extreme cold waves have decreased at rates of 4.5 stations · (10a)^-1, 2.8 stations · (10a)^-1, and 0.18 stations · (10a)^-1, respectively, with the frequencies of short-duration events (24 h and 48 h) decreasing while long-duration events (72 h) increased. The frequency was highest in the 1960s, followed by a fluctuating decrease, reaching its lowest point in the 1990s, and then fluctuating and increasing since the 2000s. An abrupt change in cold waves and strong cold waves occurred in the late 1980s. (4) The atmospheric circulation before and after the abrupt change of cold waves in Ningxia exhibits completely opposite distribution characteristics, with the circulation pattern being favorable for the active southward movement of polar cold air before the change and unfavorable afterward. However, the key influencing systems of cold waves in Ningxia during 1961–2020 and before/after the abrupt change are relatively consistent. When the Ural blocking high is abnormally strong, the East Asian trough is strong, the height field over the western coast of Europe is abnormally low, cyclonic circulation dominates to the west of Lake Baikal, and the polar cold high is active, it is conducive to the active southward movement of cold air in the mid-high latitudes, resulting in more cold waves in Ningxia, and vice versa.

Full Text

Abstract

Based on daily minimum temperature observations from Ningxia and monthly reanalysis data of geopotential height, sea level pressure, and wind fields for the period 1961–2020, this study analyzes the spatiotemporal evolution characteristics of cold waves, strong cold waves, and exceptionally strong cold waves of different durations in Ningxia over the past 60 years, and further reveals the associated atmospheric circulation anomalies. The results show that: (1) Cold waves of different intensities and durations exhibit a consistent spatial distribution pattern of "more in the east and north, less in the west and south," which is related to the paths of cold air and the topography of Ningxia. (2) The frequencies of cold waves, strong cold waves, and exceptionally strong cold waves account for 71.7%, 22.6%, and 5.7% of the total annual cold wave frequency, respectively. Cold waves are dominated by short-duration events, while strong and exceptionally strong cold waves have comparable proportions across different durations. All types of cold waves show a monthly increasing trend from October to April. (3) Cold waves, strong cold waves, and exceptionally strong cold waves have decreased at rates of 4.5, 2.8, and 0.18 events per decade, respectively, with short-duration events showing significant reductions while long-duration events have increased. All three categories fluctuated and declined from the 1960s to the 1990s, reaching minima in the 1990s, then increased after the 2000s. Cold waves and strong cold waves experienced a climatic shift around the late 1990s. (4) The atmospheric circulation patterns before and after this shift show completely opposite characteristics: the pre-shift circulation favored active southward movement of polar cold air, while the post-shift pattern did not. However, the key influencing circulation systems remained consistent. When the Ural blocking high is abnormally strong, the East Asian trough is deep, the height field over western Europe is abnormally low, cyclonic circulation dominates west of Lake Baikal, and the polar cold high is active, conditions favor the southward intrusion of mid-high latitude cold air, resulting in more cold waves in Ningxia, and vice versa.

Keywords: cold wave; spatiotemporal evolution; atmospheric circulation; anomaly analysis; Ningxia

Introduction

Cold waves are hazardous weather events in which large-scale cold air from high latitudes reaches a certain intensity under specific synoptic conditions and rapidly invades mid- and low-latitude regions. These events are accompanied by sharp temperature drops, rapid pressure increases, and strong winds, often causing heavy snow, gales, and freezing rain that inflict significant damage on agricultural production, transportation, the national economy, and public health [1-3]. Against the backdrop of global warming, rising temperatures have led to more unstable climates and more fragile ecosystems, with the intensity of extreme cold events, including cold waves, increasing in recent years [4-6]. For instance, the large-scale cold wave in early January 2016 broke historical temperature records across many regions of China, with southern China experiencing rare persistent low-temperature, rain, snow, and freezing weather that affected nearly 200 million people. In February 2021, a major cold wave struck the United States, bringing extreme cold to multiple regions and causing power outages in 5 million households [7-8]. As one of the most important extreme weather events in China and globally, cold waves cause enormous economic losses and pose serious threats to life and property, making it essential to study their variation patterns and causes.

Since the 1950s, Tao Shiyan [9] has conducted extensive research on the origins, paths, and evolution of East Asian cold waves, establishing that Chinese cold waves mainly originate from the Arctic Ocean, Siberia, and Mongolia, and primarily follow three invasion paths, laying the theoretical foundation for early cold wave forecasting. Subsequent studies have focused on two main aspects: evolution characteristics [10-14] and causal analysis [15-20]. Wang Zunya and Ding Yihui [10], Qian Weihong and Zhang Weiwei [11], and Wei Fengying [12] found that under climate warming, cold wave frequency in China has significantly decreased temporally, most notably in winter, followed by autumn and spring, and spatially decreasing from north to south. Regional studies by Lin Jing et al. [13], Yan Qi et al. [14], and Hu Chunli et al. [15] on Fujian, Liaoning, Northeast China, and the Beijing-Tianjin-Hebei region revealed that different regions show varying evolution trends due to geographical factors and climatic conditions. To understand the causes of cold wave anomalies, research has analyzed dynamic reasons for strong cold air accumulation [16], atmospheric circulation [17-18], and external forcings [19-20]. Qiao Xuemei et al. [17] found that cold wave frequency changes in northern China are directly related to atmospheric circulation, primarily influenced by the Arctic Oscillation and the intensity and area of the polar vortex over Asia. Liu Meijiao et al. [18] further noted that more cold waves occur when the Arctic Oscillation index is in its negative phase. Tang Mengqi et al. [19] revealed that rapid sea ice reduction in the Novaya Zemlya region of the Arctic makes it difficult for cold air to move southward, leading to fewer spring cold waves in Northeast China.

Ningxia is located in the transition zone between semi-arid and arid regions, with the Liupan Mountains in the south (average elevation above 2500 m) serving as a natural barrier for the Guanzhong Plain and an important watershed in northern China. The Helan Mountains in the north (elevation 1600–3000 m) weaken the eastward intrusion of cold air from the northwest while blocking the westward advance of humid southeast monsoons. These unique geographical features and complex climatic conditions make Ningxia a high-quality crop production base and also one of the regions most severely affected by cold wave disasters. Previous research on cold waves in Ningxia has focused on individual event diagnosis and characteristic analysis of different intensity levels, without examining the evolution characteristics of different duration events [21-23]. Since cold waves of different durations and intensities have varying impacts, this study uses daily temperature observations from 1961–2020 and concurrent reanalysis data of geopotential height, sea level pressure, and wind fields to analyze the spatiotemporal evolution characteristics of different intensities and durations of cold waves in Ningxia, and further reveals the associated atmospheric circulation anomalies, providing insights for cold wave prediction and disaster prevention in Ningxia.

1.1 Study Area Overview

Ningxia is located in inland China, far from the ocean, with complex terrain and elevations above 1000 m throughout the region (104°17 –107°39 E, 35°14 –39°23 N). The terrain gradually slopes from southwest to northeast, with higher elevation in the south and lower in the north, descending in a stepwise pattern. The region has a typical continental climate with insufficient moisture sources and uneven precipitation distribution. Data from 25 meteorological stations are selected for analysis (Fig. 1 [Figure 1: see original paper]).

1.2 Data Sources

Daily minimum temperature data from 25 meteorological stations in Ningxia are used, along with monthly reanalysis data of 500 hPa and 700 hPa geopotential height, sea level pressure, and wind fields from the NCEP/NCAR dataset (spatial resolution 2.5°$×$2.5°, covering 0°–90°N, 0°–180°E), with climate values based on the 1991–2020 average.

1.3 Research Methods

According to the national standard "Cold Wave Grade" (GB/T 21987–2017), cold waves are classified into three types in this study. When a process meets multiple duration criteria simultaneously, it is classified based on the shortest duration achieved. For analysis, spatial distribution features are examined using the frequency of cold waves, strong cold waves, and exceptionally strong cold waves of different durations at individual stations in Ningxia (in events). Temporal variation features are analyzed using the frequency of different durations and intensities across all 25 stations (in station-events). Common meteorological statistical methods including linear regression, moving average, and moving t-test are applied to analyze temporal variation characteristics. Correlation analysis and composite analysis [24] are used to reveal atmospheric circulation anomaly patterns associated with cold waves in Ningxia.

2.1 Spatial Distribution Characteristics of Cold Wave Frequency

The spatial distribution patterns of cold wave frequency of different intensities in Ningxia all show regional characteristics of "more in the east and north, less in the west and south" (Fig. 2 [Figure 2: see original paper]). Cold waves have two high-frequency centers, with Yanchi recording the highest frequency at 5.1 events, and Haiyuan and Jingyuan the lowest at 1.5 events. Strong cold waves also have two high-frequency centers in Yanchi (1.7 events) and Shizuishan (1.6 events), with Wuzhong, Zhongning, and Jingyuan the lowest at 0.75 events. Exceptionally strong cold waves occur much less frequently, with Yanchi as the only high-frequency center at 0.8 events, and Zhongning, Zhongwei, and Yinchuan the lowest at 0.2 events. The spatial distribution of different durations for each intensity level is consistent with the overall intensity pattern. The "east-north versus west-south" pattern is primarily due to cold air paths and topography. Cold air affecting Ningxia follows four paths: northwest-north, northwest, west, and north, all invading from the north. The western part is shielded by the Helan Mountains at the border with Inner Mongolia, while the southern part is blocked by the Liupan Mountains spanning Shaanxi, Gansu, and Ningxia, weakening the cold air in these regions.

2.2.1 Interannual and Interdecadal Variations

There are clear quantitative differences in the annual average frequency of different intensity cold waves: cold waves are most frequent at 4.5 station-events, followed by strong cold waves at 1.4 station-events, and exceptionally strong cold waves at 0.4 station-events, accounting for 71.7%, 22.6%, and 5.7% of the annual total, respectively. In terms of duration, cold waves are dominated by short-duration events (24 h and 48 h), which account for 61.0% and 32.4% of cold waves, respectively, while 72 h events are rare at only 6.6%. Strong and exceptionally strong cold waves have more balanced duration distributions, with 24 h events accounting for 46.7% and 44.6%, respectively, 48 h events for 32.7% and 32.3%, and 72 h events comprising a substantial proportion at 20.6% and 23.1%, respectively. This indicates that while weaker cold waves are mainly short-duration, stronger events have equally important short and long durations, particularly for exceptionally strong cold waves.

All three intensity categories show linear decreasing trends: cold waves at -4.5 events per decade, strong cold waves at -2.8 events per decade, and exceptionally strong cold waves at -0.18 events per decade (Table 2). The trends for cold waves and strong cold waves pass the 0.05 significance level, while exceptionally strong cold waves pass the 0.1 level. By duration, short-duration (24 h and 48

h) events show significant decreasing trends, while long-duration (72 h) events show increasing trends. Thus, short-duration cold waves of all intensities have decreased significantly in Ningxia, while long-duration events have increased.

Cold waves, strong cold waves, and exceptionally strong cold waves all show fluctuating decreasing trends, with reductions from the 1960s to the 1990s, minima in the 1990s, and increases since the 2000s (Fig. 3 [Figure 3: see original paper]). The 1960s had the highest frequencies: 6.3, 2.5, and 0.6 station-events for the three types, respectively. The 1990s had the lowest frequencies at 3.3, 1.0, and 0.3 station-events. The 2000s showed increases to 4.5, 1.3, and 0.4 station-events. The interdecadal variation of exceptionally strong cold waves is more pronounced, with three peaks in the 1960s, 1980s, and 2000s, all reaching 0.5 station-events. The variation patterns for different durations match those of their respective intensity categories, with all durations showing "decrease then increase" trends and passing the 0.05 significance level in the 1990s, consistent with the pronounced global warming since the late 1990s [25].

Moving t-tests reveal that cold waves and strong cold waves experienced a climatic shift around 1993, while exceptionally strong cold waves show no significant shift. This "decrease then increase" pattern is consistent with findings by Ma Li et al. [26].

2.2.2 Monthly Variation Characteristics

Cold waves in Ningxia mainly occur from October to April, with few events in other months (Fig. 5 [Figure 5: see original paper]). The total frequencies of cold waves and strong cold waves show a monthly increasing trend from October to April, while exceptionally strong cold waves increase from October to January then decrease. October, November, December, January, March, and April each account for over 10% of annual frequencies for all intensities. Peak months vary by duration: exceptionally strong cold waves peak in December, while other durations peak in November. Specifically, cold waves occur most frequently in November (21.7%), strong cold waves in November (20.6%), and exceptionally strong cold waves in December (18.5%).

2.3 Atmospheric Circulation Anomalies Associated with Cold Waves in Ningxia

Atmospheric circulation is the direct dynamic factor determining cold wave climate variability. The above analysis shows significant temporal evolution characteristics, with a climatic shift in the late 1990s for cold waves and strong cold waves. Therefore, this section examines the circulation causes of interannual and interdecadal cold wave variations using the full period (1961–2020), pre-shift period (1961–1990), and post-shift period (1991–2020). Note that "cold waves" in this section refers to the total annual cold wave events including all three intensity categories.

2.3.1 Correlation Between Cold Waves and Atmospheric Circulation

Cold waves show significant correlations with atmospheric circulation in mid-high latitudes. The correlation patterns for the full period and pre-shift period are consistent, while the post-shift period shows some differences, though the key high-correlation regions remain similar (Fig. 6 [Figure 6: see original paper]). At 500 hPa, significant "negative-positive-negative" correlation centers exist over western Europe, the Ural Mountains, and west of Lake Baikal. The sea level pressure field shows similar "negative-positive-negative" centers over western Europe, high latitudes from the polar region to Lake Baikal, and Northeast China. At 700 hPa, cold waves show significant positive correlation with northerly winds west of Lake Baikal. Post-shift correlations show significant centers over western Europe, the Urals, and near Lake Baikal, but the positive correlation zone from the polar region to Lake Baikal is more extensive.

2.3.2 Atmospheric Circulation Patterns Before and After the Cold Wave Shift

Composite analysis reveals opposite circulation patterns before and after the shift (Fig. 7 [Figure 7: see original paper]). During 1961–1990, the 500 hPa circulation was controlled by negative anomalies in mid-high latitudes, with negative centers over the Barents Sea, Mediterranean, Lake Baikal and its southern region. A ridge over Lake Baikal and a trough over the Sea of Japan placed Ningxia under northwesterly flow ahead of the ridge, with a deeper-than-normal East Asian trough favoring southward cold air movement. The sea level pressure field showed positive anomalies over the polar region and negative anomalies over the Caspian Sea and mainland China, with a north-high-south-low configuration favoring a strong Siberian High and winter monsoon. At 700 hPa, cyclonic circulation south of Lake Baikal combined with southwestern flow from the Bay of Bengal strengthened the northwesterly flow delivering cold air to Ningxia.

After 1991, the pattern reversed: 500 hPa showed positive anomalies with a weaker East Asian trough, while the sea level pressure field showed north-low-south-high pressure in mid-high latitudes, and the 700 hPa wind field lacked northerly flow, inhibiting southward cold air movement. The difference fields between the two periods show significant centers passing the 0.05 significance level, indicating a substantial circulation regime shift. The pre-shift circulation favored active southward movement of polar cold air, resulting in more cold waves in Ningxia, while the post-shift pattern was unfavorable.

2.3.3 Atmospheric Circulation in Anomalous Cold Wave Years

To further reveal the circulation causes of interannual cold wave anomalies, typical anomalous years were selected for composite analysis (Table 4). Comparing the difference fields between high-frequency and low-frequency years (Fig. 8 [Figure 8: see original paper]) with the correlation patterns (Fig. 6 [Figure 6: see original paper]), the difference centers correspond well to the high-correlation centers, with consistent key circulation systems across periods. At 500 hPa, a "negative-positive-negative" wave train exists in mid-high latitudes, with negative centers over western Europe and from Northeast China to the Sea of Japan, and a positive center over the Urals, indicating that high-frequency years feature a stronger Ural blocking high and deeper East Asian trough with more active cold air. The sea level pressure field shows negative centers over the Mediterranean and most of China and a positive center around Novaya Zemlya, favoring active southward movement of polar cold high pressure. At 700 hPa, anomalous cyclonic circulation south of Lake Baikal and over the Sea of Okhotsk favors the formation of two northerly flow branches west of Lake Baikal, transporting cold air to Ningxia.

The pre-shift pattern is similar, while the post-shift pattern shows some differences in sea level pressure and wind fields. In high-frequency years after 1991, the polar and Tibetan Plateau cold high systems are stronger, and the powerful cyclonic circulation west of Lake Baikal at 700 hPa favors strong northerly flow invading Ningxia.

In summary, although circulation patterns before and after the shift show some differences, the key influencing systems remain consistent. When the Ural blocking high is abnormally strong (weak), the East Asian trough is deep (shallow), the 500 hPa height field over western Europe is low (high), polar surface cold high pressure is active (inactive), and cyclonic (anticyclonic) circulation dominates west of Lake Baikal, conditions favor (inhibit) the southward movement of mid-high latitude cold air, resulting in more (fewer) cold waves in Ningxia (Fig. 9 [Figure 9: see original paper]).

3 Conclusions

(1) Cold waves of all intensities in Ningxia show a "more in the east and north, less in the west and south" distribution pattern, with high-frequency centers in Yanchi, followed by Shizuishan, and lowest frequencies in Wuzhong, Zhongning, and Jingyuan. The frequencies of cold waves, strong cold waves, and exceptionally strong cold waves are 4.5, 1.4, and 0.4 station-events, respectively, accounting for 71.7%, 22.6%, and 5.7% of the annual total. Cold waves are dominated by short-duration events (24 h and 48 h), while strong and exceptionally strong cold waves have more balanced duration distributions.

(2) Cold waves, strong cold waves, and exceptionally strong cold waves have decreased at rates of 4.5, 2.8, and 0.18 events per decade, respectively, with short-duration events decreasing significantly while long-duration events have increased. All categories fluctuated and decreased from the 1960s to the 1990s, reached minima in the 1990s, then increased after the 2000s. Cold waves and strong cold waves experienced a climatic shift in the late 1990s.

(3) Cold waves occur mainly from October to April, accounting for 99%, 98%,

and 95% of annual frequencies for the three intensity categories, respectively. Monthly frequencies increase from October to December then decrease from January to April. Peak months vary by duration: exceptionally strong cold waves peak in December, while other durations peak in November.

(4) Influenced by global warming, the atmospheric circulation patterns before and after the cold wave shift in Ningxia show completely opposite characteristics. The key influencing circulation systems are consistent: when the Ural blocking high is abnormally strong, the East Asian trough is deep, the height field over western Europe is abnormally low, cyclonic circulation dominates west of Lake Baikal, and the polar cold high is active, conditions favor the southward movement of mid-high latitude cold air and more cold waves in Ningxia, and vice versa.

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Note: Figure translations are in progress. See original paper for figures.