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Causes of the extreme cold event in December 2023 on Eastern China

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Keywords: extreme cold event, Eastern China, weakening of jet stream, AO, SH, EOF

Abstract

An extreme cold event outbreaks in Eastern China (EC) in December 16–22, 2023. Its maximum intensity (−8.30 °C) and duration (7 days) are in the second place in December during 1980–2023. In Early Stage (December 6–10), surface air temperature (SAT) anomalies reach the highest at 6.77 °C, exceeding mean value by two standard deviations. The variation of SAT anomalies (differences of SAT anomalies between the last day and the first day for a given period) is 0.60 °C. In Development Stage (December 11–15), SAT anomalies begin to decline but remain positive. In Outbreak Stage (December 16–22), the variation of SAT anomalies reaches a minimum of −3.17 °C, reflecting the cooling of EC. From December 1, cold air gradually gathers in Siberia under the influence of Arctic high moving southward. Cold air is locked in Siberia due to negative anomalies of geopotiential height (GH) and the westerlies anomalies between 40°–50°N. On December 11, these negative GH anomalies begin to move southeastward, and the westerlies anomalies weaken to a easterlies. From December 16–22, EC experiences an extreme cold event due to the southward of Arctic high and the eastward of Ural and Okhotsk high. On the basis of the zonal wind index (ZI) phase changes from negative to positive and the jet stream moves southeastward, the strong (weak) jet stream is spotted to block (promote) the southward of cold air. Linear regression shows that negative Arctic Oscillation (AO) conducts to the concentration of cold air in Siberia. Positive Siberia High (SH) pushes cold air to EC. SAT anomalies decrease by 2.29 °C in EC with the increase of 1 unit for SH. In empirical orthogonal function (EOF) analysis, EOF1 (28.07%) is characterized by warm Arctic and cold Siberia (WA-CS), which reflects the effect of SH on the occurrence of extreme cold events.

1. Introduction

Human influence has warmed the atmosphere, ocean, and land. This climate change is already affecting many weather and climate extremes in every region across the globe (IPCC 2023). The extreme cold event is a type of climate extremes occurring in winter, which mainly reflects in the rapid drop for temperature with heavy wind, rainfall, and snowfall weather (Hansen et al 2014, Liu *et al* 2021). It causes disasters in terms of human security, agricultural production, transportation, and energy supply (Smith and Sheridan 2019, Qi *et al* 2022, Meng *et al* 2023). The rate of Arctic warming has increased, while temperature in min-latitude continents has had a downward trend in Northern Hemisphere since 1990 (Cohen *et al* 2014). This phenomenon of Arctic warming faster than global average is called Arctic amplification (Serreze and Francis 2006, Cohen *et al* 2014, Cohen *et al* 2020). Besides, the winter temperature also has significant changes in China. It shows an overall increasing trend during the past six decades, while it remains stable and even decreases slightly since the winter of 2006 (so-called the warming hiatus period) (Fu and Ding 2021). As the changes of temperature in Arctic and mid-latitudes of Northern Hemisphere, extreme cold events increase at mid-latitudes (Cellitti *et al* 2006, Cohen *et al* 2018, Fu and Ding 2021, Zhang *et al* 2023). For example, extraordinarily frequent and long-lasting snowstorms affected China in January 2008 (Wen *et al* 2009). During the winter of 2009/10, four major cold surges and several heavy snowfall events, including a record-breaking event on January 4, 2010, are observed in Korea (Park *et al* 2010). In late January 2012, a strong cold anomaly covering almost entire of Europe, Mongolia, and Northeastern China, lasts for about 3 weeks (Lan and Chen 2013). In January 2016, a historic snowstorm hit the Northern and Eastern United States (Cui and Qiao 2016). Moreover, an unprecedented cold wave, called the 'boss level' cold wave, occurs and leads to record-breaking low temperature in many regions of East Asia during this period (Ma and Zhu 2019, Si *et al* 2021). Three impactful extreme cold events successively occur across East Asia and North America during the mid-winder of 2020/21 (Zhang *et al* 2022). In addition, an extreme cold event occurs in Eastern China (EC) in December 2023 (https://news.cyol.com/gb/articles/2023-12/20/content_773E0vUeEN.html).

Previous studies have shown the direct factors for the occurrence of extreme cold events are relevant to the atmosphere circulation pattern (Wen *et al* 2009, Ma and Zhu 2019, Yu *et al* 2022, Yao *et al* 2023). Wen *et al* (2009) demonstrate that the conditions of December Middle East jet stream and Arctic Oscillation (AO) exhibit stronger precursory signals of the variability of January temperature over Central-Southern China. Mao *et al* (2007) point out when the strength of East Asian jet stream (EAJS) is strong, its position is northward, causing China to cool from north to south. While other investigation indicate that the weakening and collapse of jet stream increases the probability of extreme cold events in mid-latitudes (Francis and Vavrus 2012, Yao *et al* 2017). In addition, during the years when negative AO leads to cold anomalies in East Asia, the negative AO induces an enhanced Siberia high (SH) (Wu and Wang 2002, Song and Wu 2018). Ma and Zhu (2019) have analyzed an extreme cold wave in January 2016 by investigating the atmosphere circulation pattern and comparing the observation with the simulation of the MIROC5 model. They show that the strong anomalies of Ural blocking high and SH cause the cold wave in East Asia (Ma and Zhu 2019). In terms of the extreme cold events across North America and Eurasia in 2022, they are closely related to the establishment of Alaska blocking and Ural blocking (Yao *et al* 2023). In summary, the evolution of atmosphere circulation that accompanies each extreme cold event is different. For this, we investigate the recent extreme cold event in EC in December 2023, to research the condition of jet stream and the impact of AO and SH on this event.

This study is structured as follows. Section 2 describes the data and methods. Analysis of this extreme cold event and the impact by AO and SH are in section 3. The conclusion and discussion are in section 4.

2. Data and methods

2.1. Data

In this study, we use the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) datasets on pressure and single levels (Hersbach *et al* 2023a, Hersbach *et al* 2023b). Since the difference between daily mean and hourly data for temperature is small (less than 1 °C) and highly correlated ($r = 0.98$) in December 2023, we use the hourly data at UTC 00:00 to represent daily data. The pressure levels datasets include geopotential, zonal wind, and meridional wind at 500 hPa. The single levels datasets include 2m temperature and mean sea level pressure (SLP). These variables are in December from 1980 to 2023, with $0.25° \times 0.25°$ grids. We use the 2m temperature to represent the surface air temperature (SAT). The geopotential height (GH) used in this study is calculated by dividing geopotential by gravitational acceleration ($g = 9.8\ m^{*}s^{-2}$). Referring to Ting *et al* (1996), the zonal wind index (ZI) is defined as the normalized difference of 35°N, 60°–120°E and 55°N, 60°–120°E in the 500 hPa zonal-mean zonal wind. It represent the intensity of jet stream. Positive (negative) values of ZI indicate stronger (weaker) westerlies at 35°N relative to 55°N, which means cold air passes through (is blocked in) Siberia. The mean SLP is used to calculate the daily SH index, which is defined as the normalized regional mean SLP between 40°–65°N, 80°–120°E (Cheung and Zhou 2015). The daily AO index used in this study is from the National Weather Service Climate Prediction Center (Higgins *et al* 2002), it is constructed by projecting the daily 1 000 hPa height anomalies poleward of 20°N onto the loading pattern (defined as the leading mode of Empirical Orthogonal Function (EOF) analysis of monthly mean 1 000 hPa height during 1979–2000 period) of the AO.

2.2. Definition for extreme cold events and variation of SAT anomalies

An extreme cold event is defined as follows. In a continuous period, it begins on a date when the SAT anomaly falls below its 10th percentile for December from 1980 to 2023, and it ends on a date when the SAT anomaly reaches the minimum. We divide the extreme cold event in this study into three stages: the Early Stage

(December 6–10), the Development Stage (December 11–15), and the Outbreak Stage (December 16–22). This extreme cold event, which corresponds to the definition given above, occurs in the Outbreak Stage. The two indicators of extreme cold events are also defined: the maximum intensity (the lowest SAT anomalies in the event), and the duration (the ending date minus the beginning date then plus 1).

In this study, the variation of SAT anomalies (differences of SAT anomalies between the last day and the first day in a given period) are used to indicates the temperature change during each stage of the investigated extreme cold event.

2.3. Linear regression

Linear regression analysis estimates the contributions of the AO and SH to the SAT anomalies in December, respectively. Based on the linear regression results, the different impacts of the AO and SH can be quantitatively evaluated. The regression equation is:

$$T_i = a_0 + a_1 I + \varepsilon \quad (1)$$

Where T_i represent the dependent variable of SAT anomalies in December from 1980 to 2023, a_0 and a_1 are the regression model parameters, I is represented by AO or SH, ε is the error term.

2.4. Empirical orthogonal function analysis

Empirical orthogonal function (EOF) analysis is used to analyze the spatial and temporal variability of single geophysical fields (Thompson and Wallace 1998). In this study, monthly SAT anomalies in December from 1980 to 2023 are calculated to examine the temperature evolutionary patterns by EOF method. The spatial distribution mode is a function of the space, and the time series is given in the form of principal component (PC) value. We first calculate the monthly SAT anomalies. Then, monthly SAT anomalies in December from 1980 to 2023, one span of 44 months is used to perform the EOF analysis, extracting spatial modes and corresponding time series.

3. Results

3.1. The characteristics of the extreme cold event in EC on December 2023

To describe the characteristics of this extreme cold event in EC, SAT anomalies are shown in figure 1 in multiple ways. In Early Stage, SAT anomalies are mainly positive in EC (20°–45°N, 110°–120°E, the red boxes in figures 1(a)–(f)), and the cold air is mainly located in Eastern European Plain and Siberia. In Development Stage, the cold air begins to invade southeastward, SAT anomalies become negative in northern EC. In Outbreak Stage, the cold air continues to move southeastward, SAT anomalies are all negative in EC (figures 1(a)–(c)). Figures 1(d)–(f) show the variation of SAT anomalies in three stages. In Early Stage, SAT mainly decreases in Siberia to Okhotsk Sea and variation of SAT anomalies is 0.60 °C in EC. In Development stage, there is a warming from Siberia to Eastern European Plain, while cooling occurs in EC. In Outbreak Stage, the warming of Siberia and Eastern European Plain becomes further amplified, and the cooling of EC is further enhanced with a variation of SAT anomalies at −3.17 °C.

In the time series of December 2023, SAT anomalies reach a maximum of 6.77 °C on December 7, exceeding the mean value by two standard deviations. They change into negative on December 16 and begin to warm up after reaching a minimum of −8.30 °C on December 22 (figure 1(g)). In addition, SAT anomalies in Outbreak Stage and extreme cold events in December from 1980 to 2023 are examined in figures 1(h)–(i). The longest extreme cold event happens during December 18–29, 1984, with a maximum intensity (−8.12 °C) and duration (12 days) (figure 1(i)). In terms of the event of highest maximum intensity, it happens during December 27–29, 1992. Its maximum intensity is −9.3 °C and duration is 3 days (figure 1(i)). This extreme cold event happens earlier than these two significant events with a mean SAT anomaly at −6.31 °C (figure 1(h)). And its both maximum intensity (−8.30 °C) and duration (7 days) are the second in December from 1980 to 2023 (figure 1(f)).

3.2. The anomalies of atmosphere circulation during three stages for this extreme cold event

To investigate the different characteristics of atmospheric circulation anomalies in three stages, the anomalies of GH, wind fields, zonal wind, and meridional wind at 500 hPa are analyzed in figure 2. In Early Stage, positive GH anomalies with an anticyclone are in Arctic. Negative GH anomalies with a cyclone are in Siberia. This GH structure characterizes the negative phase of AO. Positive GH anomalies exist in the Okhotsk Sea (figure 2(a)). In addition, there are westerlies anomalies between 40°–50°N and northerlies anomalies from high to low latitude in 60°–90°E (figures 2(d) and 2(g)). The ZI is −0.65 and jet stream is mainly located in 40–50°N, 60–120°E (figure 2(d)). As a result of this atmospheric circulation distribution, cold air moves southward from Arctic and

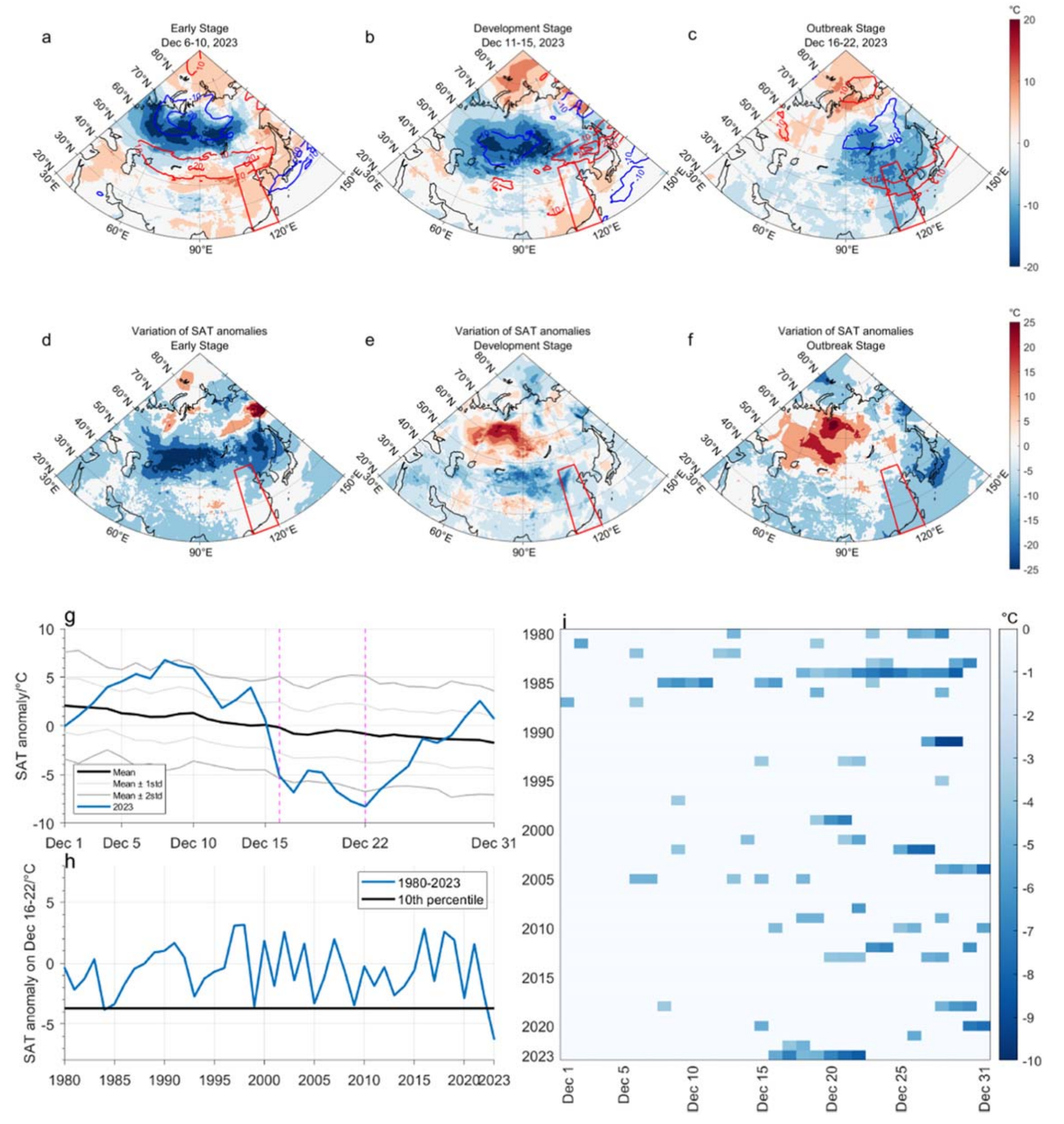

Figure 1. The anomalies of SAT (shaded) and zonal wind at 500 hPa (contour) in three stages for this extreme cold event (a)–(c). The variation of SAT anomalies in three stages (d)–(f), the red boxes represent EC (20°–45°N, 110°–120°E). Time series of regional mean of SAT anomalies in EC in December 2023 (g), the area between the pink dotted lines represents the Outbreak Stage. Time series of SAT anomalies in EC on December 16–22 from 1980 to 2023 (h), the black line is the 10th percentile of SAT in December from 1980 to 2023. Calendar chart of the distribution of extreme cold events in December from 1980 to 2023 (i), the color represents the SAT anomalies for the extreme cold events. The corresponding climatological variables are in December from 1980 to 2023.

is blocked in Siberia by the westerlies anomalies (figures 1(a), 2(a), 2(d) and 2(g)). In Development Stage, the cold air begins to move from the negative GH anomalies in Siberia to Northwest China under the southward of Arctic high and Okhotsk high (figures 1(a)–(b) and 2(a)–(b)). The anticyclone starts to become unstable in Siberia (figure 2(b)). The westerlies anomalies move eastward and weaken in western Siberia. The ZI translates to positive phase (3.12) and jet stream moves eastward to 90–150°E (figure 2(e)). The southerlies anomalies appears in EC due to the southward movement of Okhotsk high, which slows down the southward movement of cold air (figures 2(b) and 2(h)). As Arctic high moves southeastward and Ural high and Okhotsk high move eastward, the meridional gradient of the zonal wind is decreasing between mid-latitude, which is reflected by the variation of ZI (−0.65, 3.12, and 2.42) and the movement of jet stream (40–50°N, 60–120°E to Northern Pacific) (figures 2(a)–(f)). Anomalous cyclone with cold air moves fully southward to EC, leading to the outbreak of this extreme cold event (figures 1(c), 2(c), 2(f) and 2(i)).

The daily anomalies of GH, zonal wind and meridional wind at 500 hPa are further investigated respectively in figure 3, to observe the evolution of atmospheric circulation anomalies of this event. On December 1, Arctic high (purple line in figure 3(b)) and cold air show a southward movement (figures 3(b) and 3(d)). The westerlies anomalies (yellow line in figure 3(c)) between 40°–50°N move eastward from 30°E (figure 3(c)). Until December

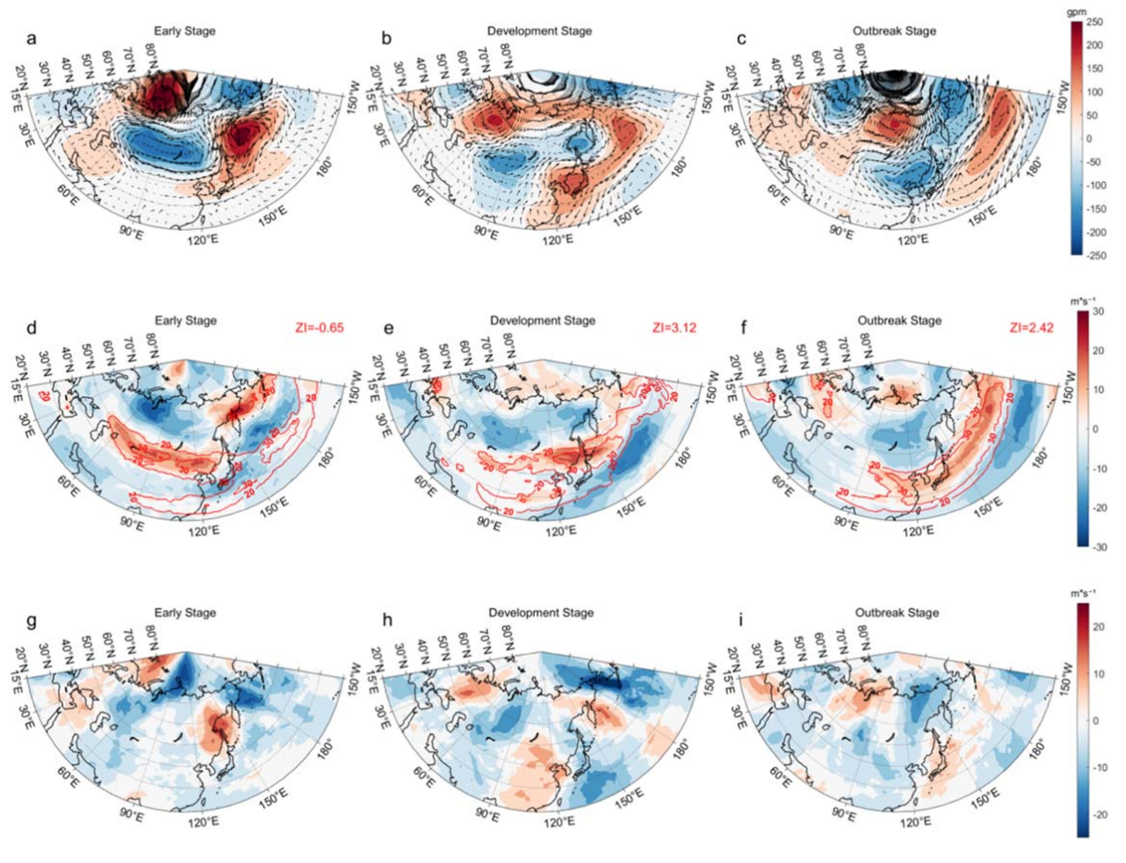

Figure 2. The anomalies of GH (shaded) and wind fields (vectors) at 500 hPa in three stages (a)–(c). The zonal wind anomalies (shaded) and westerlies (contour) at 500 hPa in three stages (d)–(f), the number in the upper right corner represents ZI value. The anomalies of meridional wind at 500 hPa in three stages (g)–(i). The corresponding climatological variables are in December from 1980 to 2023.

10, cold air remains entrenched in Siberia (figures 1(a) and 3(a)–(d)). From December 11, cold air accompanied by negative GH anomalies (orange lines in figures 3(a)–(b)) in Siberia begins to move southeastward under the eastward movement of Ural high (green line in figure 3(a)) and Okhotsk high (yellow line in figure 3(a)) (figures 1(b) and 3(a)–(b)). The easterlies (green line in figure 3(c)) and westerlies anomalies also move eastward (figures 2(d)–(f) and 3(c)). In addition, the anomalies of meridional wind are almost northerlies between 60°–120°E throughout December. Under this evolutionary situation, cold air reaches EC on December 16 and crosses on December 23 (figures 1(c) and 3(a)–(d)).

3.3. The impact of AO and SH on this extreme cold event

To investigate the impact of AO and SH on SAT anomalies during this extreme cold event, linear regression is used in figures 4(a)–(b). The AO on December 1–11 is used to regress with SAT anomalies on December 1–22, to explain the contribution of AO to the accumulation of cold air (figures 4(a) and 4(c)). The regression coefficients in figure 4(a) are multiplied by −1 which indicates the SAT anomalies in Siberia decline with the decreasing of AO (this process does not have any practical effect on the regression results). This result suggests that negative AO favors the accumulation of cold air in Siberia before the outbreak of extreme cold events. The SH on December 9–19 is used to regress with SAT anomalies on December 16–22, to illustrate the contribution of SH to the outbreak of this extreme cold event (figures 4(b) and 4(c)). In figure 4(b), the regression result shows that SAT anomalies of EC decline with the enhancement of SH. The regional mean of regression coefficients is −2.29 °C, which indicates the anomalies of SAT decline by 2.29 °C in EC when SH increases 1 unit (figure 4(c)). It suggests that negative SH is a direct influence factor on the outbreak of this extreme cold event in EC.

Finally, EOF is used to examine the long-term spatial trend of SAT anomalies in December from 1980 to 2023 (figure 5). The EOF1 passes the north test. In EOF1 (28.07%), positive values are concentrated in Arctic. Negative values are located in Siberia and northern Asia (figure 5(a)). The PC1 has an increasing trend (figure 5(b)). This distribution of warm Arctic and cold Siberia (WA-CS) is similar to the regression result in figure 4(b) (with a correlation coefficient of 0.49 between SH and PC1), which means the spatial distribution of EOF1 has some positive correlation with SH. In this mode, cold air mainly gathers in Siberia. As a background field, the distribution of EOF1 is consistent with extreme cold events. Arctic warming causes cold air to

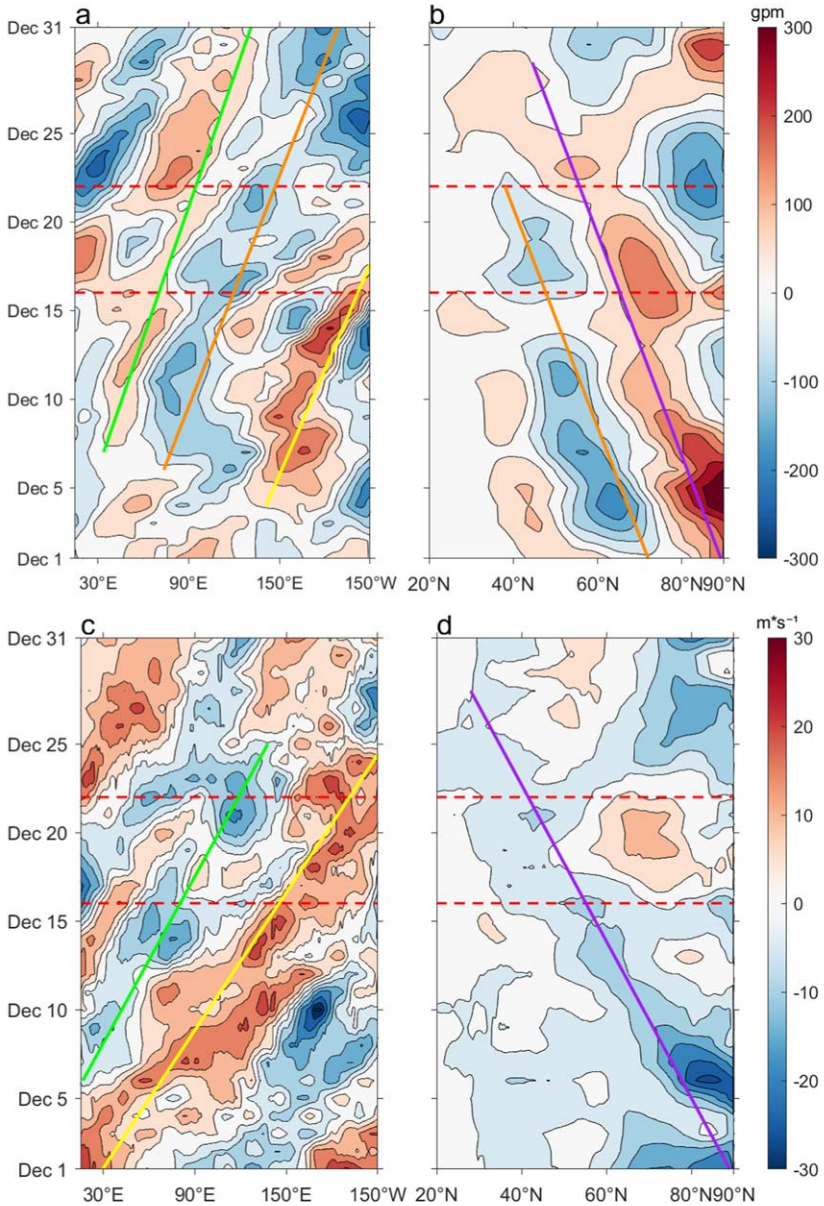

Figure 3. The Longitude-Time distribution of GH anomalies (30°–60°N mean) in December 2023 (a), the green, yellow, and orange lines represent the movement of Ural high, Okhotsk high, and low-pressure center in Siberia, respectively. The Latitude-Time distribution of GH anomalies (60°–150°E mean) in December 2023 (b), the purple and orange lines represent the movement of Arctic high and a negative GH anomalies center in Siberia, respectively. The Longitude-Time distribution of zonal wind anomalies (40°–50°N mean) in December 2023 (c), the green and yellow lines represent the movement of easterlies and westerlies anomalies, respectively. The Latitude-Time distribution of meridional wind anomalies (60°–120°N mean) in December 2023 (d), the purple line represents the movement of northerlies anomalies. The area between the red dotted lines in (a)–(d) represents the Outbreak Stage of this cold event. The level of GH and wind is at 500 hPa. The corresponding climatological variables are in December from 1980 to 2023.

concentrate in Siberia. As soon as the suitable condition of GH and wind anomalies occurs, cold air moves southward, leading to EC cold events.

4. Conclusion and discussion

This study investigates an extreme cold event in EC in December 2023 and reveals its causes. This extreme cold event has a maximum intensity for −8.30 °C and a duration for 7 days, setting a second record for the period of December 1980–2023. In Early Stage, EC is warm with a variation of SAT anomalies for 0.60 °C. Cold air is mainly located in Eastern European Plain and Siberia. In Development Stage, cold air begins to invade northern EC. SAT anomalies of EC plummet to −6.31 °C in Outbreak Stage with a variation of SAT anomalies for −3.17 °C, and it reaches a minimum of −8.30 °C on December 22. In the analysis of atmosphere circulation, GH anomalies are characterized by a high Arctic and low Siberia structure, which together with the positive

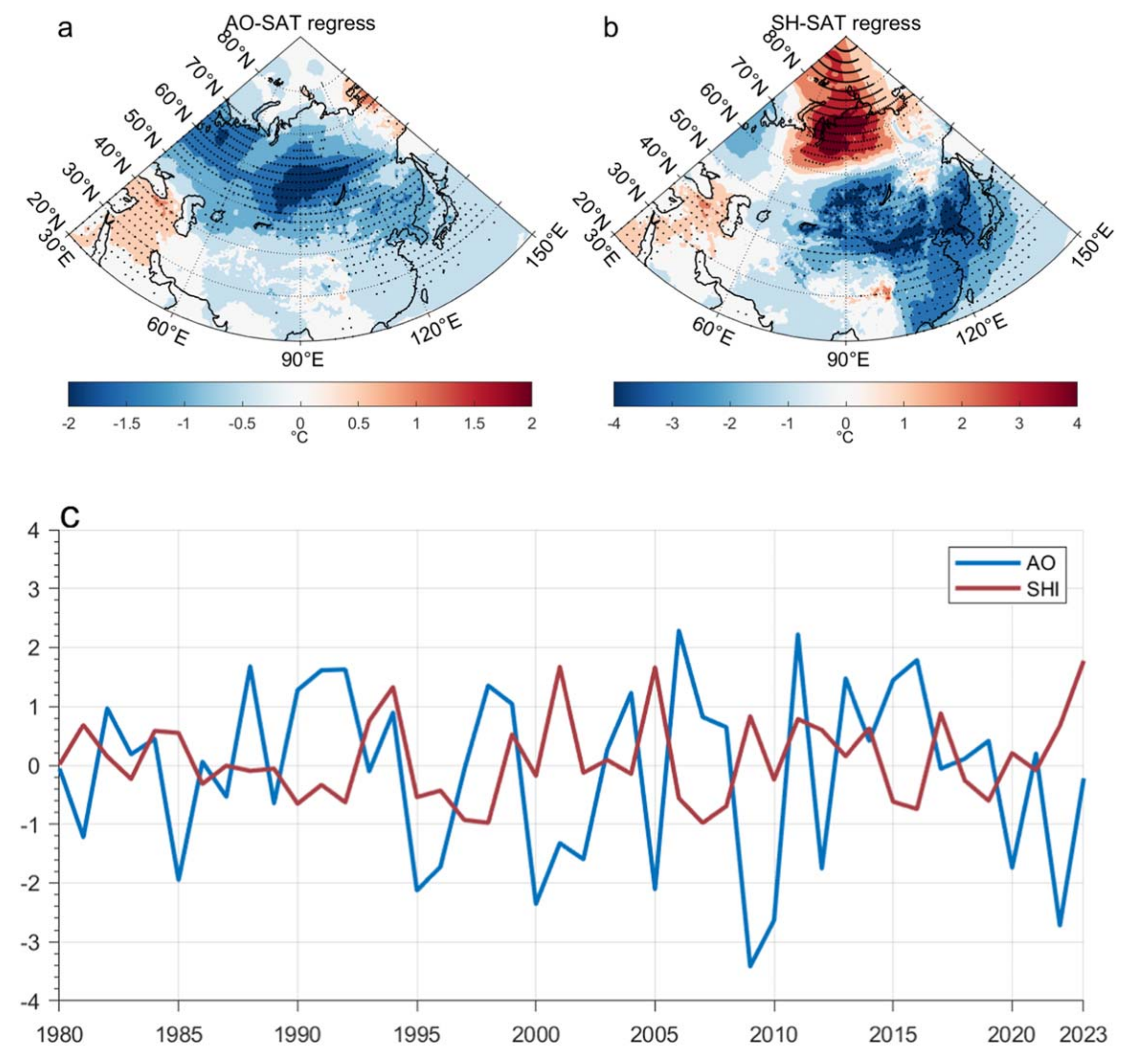

Figure 4. The distribution for regression coefficients of AO index on December 1–11 with SAT anomalies on December 1–22 from 1980 to 2022 (a), these regression coefficients are multiplied by −1. The distribution for regression coefficients of SH index on December 9–19 with SAT anomalies on December 16–22 from 1980 to 2022 (b). The time series of AO and SH from 1980 to 2023 (c). The significant areas at the 90% confidence level are dotted in the spatial distribution. The corresponding climatological variables are in December from 1980 to 2023.

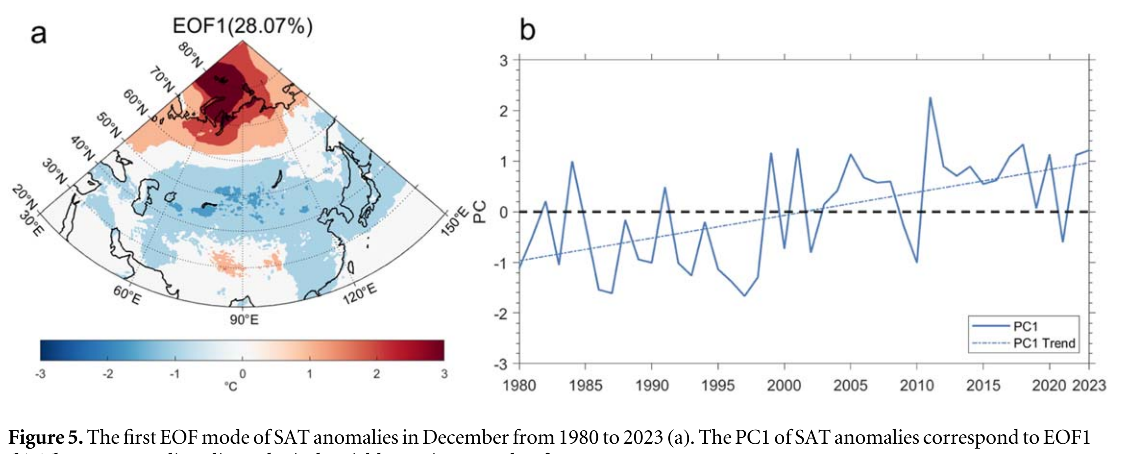

Figure 5. The first EOF mode of SAT anomalies in December from 1980 to 2023 (a). The PC1 of SAT anomalies correspond to EOF1 (b). The corresponding climatological variables are in December from 1980 to 2023.

westerlies anomalies lock cold air in Siberia in Early Stage. From December 11 (Development Stage), cold air in Siberia begins to move southeastward under the eastward movement of Ural high and Okhotsk high. The jet stream also moves southeastward from 40°–50°N, 60°–120°E. In addition, the anomalies of meridional wind are almost northerlies between 60°–120°E throughout December. With the above changes of the dynamical structure, the cold air reaches EC on December 16 and crosses on December 23. In mid-latitudes, it is also observed that the meridional gradient of zonal wind decreases, which is reflected by the ZI phase changes from negative to positive and the southeastward movement of jet stream. The variation of ZI (−0.65, 3.12, and 2.42) correspond to the characteristics of this extreme cold event, which warms first and then cools. It is obvious that strong (weak) jet stream block (promote) the southward movement of cold air from Siberia during this extreme cold event.

Linear regression shows the impacts of AO and SH on this extreme cold event. Negative AO favors the concentration of cold air in Siberia before the outbreak of this extreme cold event. And the positive SH favors the push of cold air from Siberia to EC, leading to the outbreak of this extreme cold event. The regression results also show that as SH increases 1 unit, SAT anomalies decrease by 2.29 °C in EC. In EOF of SAT anomalies, the distribution of EOF1 (28.07%) is similar to the regression results of SH. This WA-CS distribution is a mode of cold air moving southward into Siberia and EC, which reflects the effect of SH on the occurrence of extreme cold events.

By focusing on the extreme cold event in December 2023 on EC, we illustrate the weakening of the jet stream during this event, revealing the possible impact of AO and SH on it. However, the contribution of oceanic processes is uncertain. Many mathematical and climate models are also commonly used to study regional extreme weather events (Ma and Zhu 2019, Sun *et al* 2023). Therefore, it is necessary to further investigate the influence of ocean-atmosphere interactions on this extreme cold event.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview. https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml.

Conflict of interest

The authors declare that they have no conflict of interest.

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