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• **News & Views** •

# Extreme Cold Events in North America and Eurasia in November–December 2022: A Potential Vorticity Gradient Perspective

Yao YAO*[1,2], Wenqin ZHUO[3], Zhaohui GONG[2], Binhe LUO[4], Dehai LUO[1,2], Fei ZHENG[5], Linhao ZHONG[6], Fei HUANG[3], Shuangmei MA[7], Congwen ZHU[7], and Tianjun ZHOU[8]

[1]*CAS Key Laboratory of Regional Climate-Environment for Temperate East Asia*, *Institute of Atmospheric Physics*, *Chinese Academy of Sciences*, *Beijing* 100029, *China*

[2]*University of Chinese Academy of Sciences*, *Beijing* 100049, *China*

[3]*Frontier Science Center for Deep Ocean Multispheres and Earth System (FDOMES) and Physical Oceanography Laboratory*, *Ocean University of China*, *Qingdao* 266100, *China*

[4]*State Key Laboratory of Earth Surface Processes and Resource Ecology*, *Beijing Normal University*, *Beijing* 100875, *China*

[5]*International Center for Climate and Environment Science (ICCES)*, *Institute of Atmospheric Physics*, *Chinese Academy of Sciences*, *Beijing* 100029, *China*

[6]*National Institute of Natural Hazards*, *Ministry of Emergency Management of China*, *Beijing* 100085, *China*

[7]*State Key Laboratory of Severe Weather*, *Chinese Academy of Meteorological Sciences*, *China Meteorological Administration*, *Beijing* 100081, *China*

[8]*State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)*, *Institute of Atmospheric Physics*, *Chinese Academy of Sciences*, *Beijing* 100029, *China*

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ABSTRACT

From 17 November to 27 December 2022, extremely cold snowstorms frequently swept across North America and Eurasia. Diagnostic analysis reveals that these extreme cold events were closely related to the establishment of blocking circulations. Alaska Blocking (AB) and subsequent Ural Blocking (UB) episodes are linked to the phase transition of the North Atlantic Oscillation (NAO) and represent the main atmospheric regimes in the Northern Hemisphere. The downstream dispersion and propagation of Rossby wave packets from Alaska to East Asia provide a large-scale connection between AB and UB episodes. Based on the nonlinear multi-scale interaction (NMI) model, we found that the meridional potential vorticity gradient ($PV_y$) in November and December of 2022 was anomalously weak in the mid-high latitudes from North America to Eurasia and provided a favorable background for the prolonged maintenance of UB and AB events and the generation of associated severe extreme snowstorms. However, the difference in the UB in terms of its persistence, location, and strength between November and December is related to the positive (negative) NAO in November (December). During the La Niña winter of 2022, the UB and AB events are related to the downward propagation of stratospheric anomalies, in addition to contributions by La Niña and low Arctic sea ice concentrations as they pertain to reducing $PV_y$ in mid-latitudes.

**Key words:** successive cold extremes, atmospheric blocking, NAO, potential vorticity gradient, water vapor backward tracking, Arctic sea ice, La Niña

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* Corresponding author: Yao YAO
Email: yaoyao@tea.ac.cn

## 1. Introduction

From 17 November to 27 December 2022, North America, Europe, and East Asia were hit by successive extreme cold snowstorms. From 17–19 November, North America was hit by an extreme cold wave, with snowstorms hitting parts of New York State (https://edition.cnn.com/2022/11/20/weather/buffalo-new-york-great-lakes-snowstorm-sunday/index.html). From 26 November into early December, China experienced a strong nationwide cold wave. An extremely low temperature of –48.6°C was observed in Altay, Xinjiang, where heavy snowstorms and extreme cold contributed to the deaths of local residents (http://www.inewsweek.cn/society/2022-12-05/17185.shtml). In mid-December, North America and East Asia were again hit by extreme cold events. Then, around 25 December, North America experienced a "bomb cyclone", which led to the coldest Christmas in nearly 40 years and caused huge social and economic damage (https://globalnews.ca/news/9372586/us-storm-power-outages-christmas-plans/).

The frequent extreme cold weather that occurred in November and December has become a matter of great concern to both the public and the research community. Recent studies indicate that although Eurasia tends to experience more frequent cold air outbreaks and heavy snowfall during La Niña winters, a skillful seasonal forecast needs to combine information regarding the North Atlantic Oscillation (NAO), the anomalous anticyclone near the Ural Mountains, and the tendency for the occurrence of cold air invasions triggered by the synergistic effect of a warm Arctic and a cold tropical Pacific on the hemispheric scale (Luo et al., 2021; Zheng et al., 2022c). Extreme cold events in mid-latitudes in winter are a direct effect and manifestation of the weakening, collapse, and re-establishment of the westerly jet (Yao et al., 2017), which is a major weather process in winter and exerts an important impact on human health and social activities (Mu et al., 2022). The prediction of extreme cold weather at subseasonal to seasonal time scales is a great challenge due to its strong dynamic nonlinear characteristics and uncertainties (Bueh et al., 2022; Dai et al., 2022; Zhang et al., 2022b; Zheng et al., 2022a). Specific atmospheric circulation modes that cause extreme cold weather include local blocking (Bueh et al., 2022; Yao et al., 2022), the NAO (Iles and Hegerl, 2017; Li et al., 2022), and the Arctic Oscillation (Chen et al., 2013; Cohen et al., 2010; Park et al., 2011). These modes can excite significant meridional circulation anomalies, further promoting and guiding the southward movement of cold Arctic air, which affects lower latitudes.

The impact of global warming on extreme cold events has received widespread attention (Luo et al., 2021; Yao et al., 2022; Zheng et al., 2022b). While it is indisputable that global warming leads to a decrease in cold extremes in long-term climate projections, forecasting such cold extremes remains a challenge for short-term climate prediction. Some studies have also revealed the relationship between a warm Arctic and a cold continent and its influence on extreme weather from the perspective of meridional potential vorticity gradient ($PV_y$) based on a nonlinear multi-scale interaction model (Luo et al., 2019a; 2019b), which is an important indicator to reveal the occurrence of extreme cold weather. In the winter of 2020/21, extreme cold events from East Asia to North America have been widely studied (Mu et al., 2022; Zhang et al., 2022b). The physical processes and mechanisms of this extreme cold event in China have been described from a synergistic perspective (Yao et al., 2022; Zhang et al., 2022a; Zhang et al., 2022c; Zheng et al., 2022b). The predictability of three extreme cold events in East Asia has been described by Dai et al. (2022). The strong cold surge sweeping through eastern and northwestern China during 4–9 November 2021 has also been a focus of the climate research community (Zhou et al., 2022). Some studies have analyzed cold extremes from the perspective of circulation anomalies (Li et al., 2022; Li et al., 2019; Luo et al., 2016a; 2016b; Ma and Zhu, 2021; Yu et al., 2022a) and isentropic mass circulation (Yu et al., 2022b). In addition, Ma and Zhu (2023) discussed the physical process of the sharp subseasonal swing of intercontinental cold and warm extremes over North America and Eurasia. They found the North-Pacific-Oscillation-like phase transition regulated by the unprecedented SST warming in the North Atlantic to be the main process. Whether the existing mechanisms help to explain the cold extremes in the later months of 2022 remains unknown, and its elucidation is a motivating factor behind the study.

This study aims to reveal the physical mechanisms associated with the frequent occurrence of extreme cold events in November–December from the perspective of $PV_y$. The following issues are addressed: 1) What atmospheric circulation regimes accompanied these extreme cold events and what were the possible connections between them? 2) What was the physical background of these frequent extreme cold events? 3) What were the characteristics of the water moisture source pathways of the two key snowstorm processes?

## 2. Data and Methodology

### 2.1. *Datasets*

The datasets used in this study are from the latest reanalysis dataset (Hersbach and Dee, 2016) from the European Centre for Medium-Range Weather Forecasts (ERA5), including the multi-level geopotential height, horizontal wind components ($u$ and $v$), surface air temperature (SAT), and snowfall, all at a 1° × 1° spatial resolution from 1979 to 2022. In addition, the high resolution (0.25° × 0.25°) daily mean ERA5 variables, including precipitable water, vertically integrated water vapor, and vertically integrated eastward and northward water vapor transport, were derived from backward trajectory analysis

(Zhong et al., 2018). We used a modified NAO index (Li and Wang, 2003) to identify NAO cases with position-shifted mean states. Here, the NAO index in November and December 2022 is defined as the difference in the normalized daily sea level pressure averaged over the North Atlantic sector (80°W–30°E) between 30°N and 60°N. The monthly Arctic sea ice concentration (SIC) dataset was obtained from the National Snow and Ice Data Center.

### 2.2. *Methods*

As revealed from the nonlinear multi-scale interaction (NMI) model (Luo et al., 2019a; 2019b) of atmospheric blocking, the meridional gradient of the background potential vorticity ($PV_y$) is a key physical indicator for the maintenance of atmospheric blocking. The non-dimensional form of $PV_y$ in the equivalent barotropic atmosphere is expressed as $PV_y = \partial PV/\partial y = \beta - \partial^2 U/\partial y^2 + FU$ (Luo et al., 2019a), where $U$ is the non-dimensional zonal wind, $\beta$ is the non-dimensional meridional gradient of the Coriolis parameter at a given reference latitude, and $F = (L/R_d)^2$, where $L$ is the characteristic length (~1000 km) and $R_d$ ~ 1000 km is the Rossby radius deformation. When $PV_y$ is small, atmospheric blocking is characterized by weak energy dispersion and strong nonlinearity, allowing it to maintain itself for a long time. Thus, a small $PV_y$ is favorable for maintaining atmospheric blocking (Luo et al., 2019a). A Hovmöller diagram (Hovmöller, 1948) is used to show the propagation of Rossby wave packets. A spatially unbounded dynamical recycling model, developed by Dominguez et al. (2006) and further extended by Zhong et al. (2018), was applied here to quantitatively examine backward moisture trajectories and water vapor contributions in target regions. For details regarding the calculation methods and model descriptions, please refer to Zhong et al. (2018). In our analysis, the daily (monthly) anomalies are defined as the deviation of the daily (monthly) field from its climatological time mean of 1979–2020.

## 3. Extreme cold events in November and December 2022 and their physical background

### 3.1. *Time evolution of circulation regimes*

Figure 1 shows the time-mean of the 500-hPa geopotential height field and SAT anomalies for the four major extreme cold events. A blocking high formed over Alaska and peaked during 17–19 November (Fig. 1a), and the downstream low-

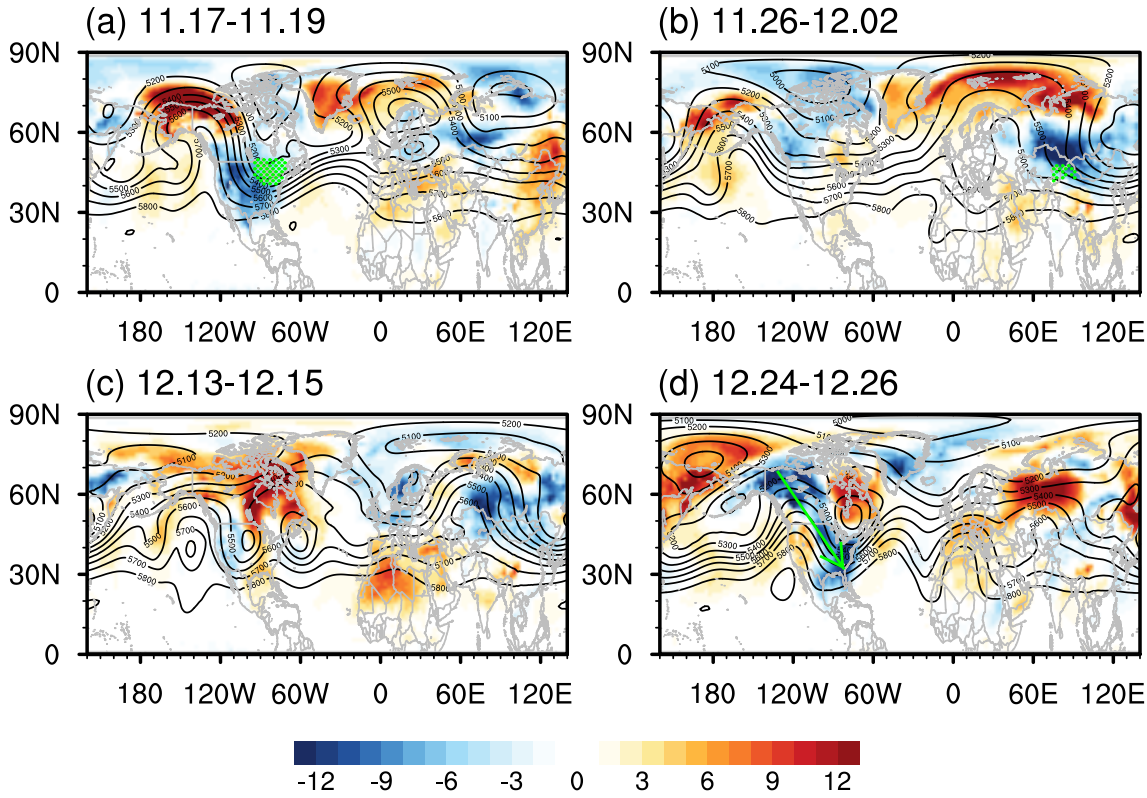


**Fig. 1.** Time-mean surface air temperature anomaly (shading, units: K) and 500-hPa geopotential height (contour, units: gpm, contour interval = 100 gpm) for the four stages: (a) 17–19 November, (b) 26 November – 2 December, (c) 13–15 December, and (d) 24–26 December that were associated with the several extreme cold events. Key snowfall areas in (a) and (b) are marked with green dots. All the anomalies are calculated relative to the mean conditions of 1979–2020.

pressure trough deepened significantly. Over the North Atlantic region, the observed pattern corresponded to a positive NAO (NAO+) structure associated with a strong zonal jet. Such a circulation regime is conducive to the polar vortex penetrating toward lower latitudes, leading to a widespread cooling process. Significant negative SAT anomalies are seen over North America, while warm anomalies were witnessed in Alaska, the Bering Strait, and parts of the adjacent Arctic Ocean. In addition, northwest New York State and the five Great Lakes, located in the center of the low-pressure trough, received significant snowfall (green dotted region) between 17–19 November, resulting in severe blizzard conditions.

One week after the North American blizzard ended, from November 26 to early December, this winter's first extreme cold wave swept through continental China, causing widespread cooling and snowfall across the country. Figure 1b illustrates the dominant circulation regime for this event, consisting of a large blocking high that appeared over Eurasia from 26 November to 2 December. The blocking further strengthened and moved eastward, translating into a Ural Blocking (UB) event, causing a trough of low pressure to further deepen downstream (Fig. S1 in the Electronic Supplementary Material, ESM). The strong push of cold air first affected Northwest China as the leading edge of the low-pressure trough reached the Xinjiang region on November 26 and caused record-breaking low temperatures and heavy snowfall in this area. Then, after November 27, the UB high continued to develop and shift to the southeast, allowing the trough of low pressure to move further to the east and south, affecting the central and southern parts of China. From November 26 to 29, the western Pacific subtropical high lifted northward and extended westward (Fig. S1 in the ESM, bold black 5880 gpm line), which was closely related to the northward movement of the southern rain band in China from November 26 to 29 (figure not shown).

In mid-December, North America and East Asia were simultaneously hit by another extreme cold process. Figure 1c shows that the circulation regime in North America exhibited a hybrid pattern. The Alaska blocking (AB) ridge is displaced significantly to the south, and the downstream low pressure caused cooling in some parts of North America. In addition, another ridge is found in the North Atlantic region, which corresponds to a negative NAO (NAO–) pattern. The low-pressure center corresponding to the NAO– was close to the eastern part of the North American continent, allowing for the two low-pressure centers to combine. This interaction led to a cooling process and a cyclonic circulation in North America that was accompanied by a tornadic outbreak. At the same time, East Asia was dominated by a lower-latitude UB ridge, which triggered a widespread cooling process.

During the subsequent Christmas season, North America was again hit by an extreme cold weather process. The associated "bomb cyclone" affected nearly the entirety of the North American continent, including Canada and the United States, causing record-breaking low temperatures and snowfall. Figure 1d shows that North America was controlled by a lower latitude AB ridge around 120°W, while a strong North Pacific blocking was present at higher latitudes to the northwest. This pattern represents a complex circulation regime where one high ridge is nested within another stronger blocking high. The two nested blocking ridges allow for a "relay effect" (as shown by the green arrow) to occur within their downstream low-pressure centers as well, allowing a large amount of cold air from the polar regions to reach the North American continent directly. Moreover, it is noted that the SAT anomalies show a west-east seesaw on synoptic-scale timescales between North America and Eurasia (Fig. 1), even though the cold events are frequent.

These major extreme cold processes have a commonality in that they are closely related to local blocking and NAO regimes, but their local details vary. Next, we employ a larger-scale view to reveal the physical processes and background linkages of these extreme cold events.

### 3.2. *A connection between local circulation regimes*

Figure 2a shows a Hovmöller diagram of daily 500-hPa geopotential height anomalies averaged over 40°–70°N from 12 November to 27 December 2022, corresponding to the propagation of a Rossby wave packet. It can be seen that there are significant and frequent propagation processes of the Rossby wave packet (shown by black arrows) from the North Pacific to the Eurasian region during the period from mid-November to the end of December. AB events were frequently generated during this period (AB1 to AB4), and the NAO shifted from a positive phase in November to a negative phase in December (the index is shown in Fig. 2b). The UB in Eurasia also shows significant activity, but is dependent on the phase of the NAO. The Rossby wave train associated with NAO+ in November is favorable for the production and maintenance of the UB (Luo et al., 2018; Luo et al., 2016b), because it exhibits a wavenumber two structure with a positive anomaly over Eurasia. In December, after the NAO transitioned to a negative phase, the Rossby wave train evolved into a wavenumber three structure, which is not conducive to the generation and maintenance of a UB, because a negative anomaly appears downstream of the North Atlantic. Therefore, UB activity decreased significantly in December. Although the frequent extreme cold events in November–December were attributed to local blocking and NAO processes, the frequent activity of these regimes is linked to the activity of the Rossby wave train, thus demonstrating their remote connection.

Figure 2b shows the temporal variations of the AB and UB intensities in addition to the NAO index. The UB and AB indexes are constructed based on the grid point where the maximum value of the respective daily blocking anticyclonic center is located, and a regional average is calculated over a 20° latitude × 60° longitude box centered on that grid point. It is found that the AB precedes the NAO+, whereas the intensification of the UB lags the decay of NAO+. In contrast, the suppressed UB activity in December is related to the presence of $NAO^{-}$. Thus, the generation and persistent intensification of a

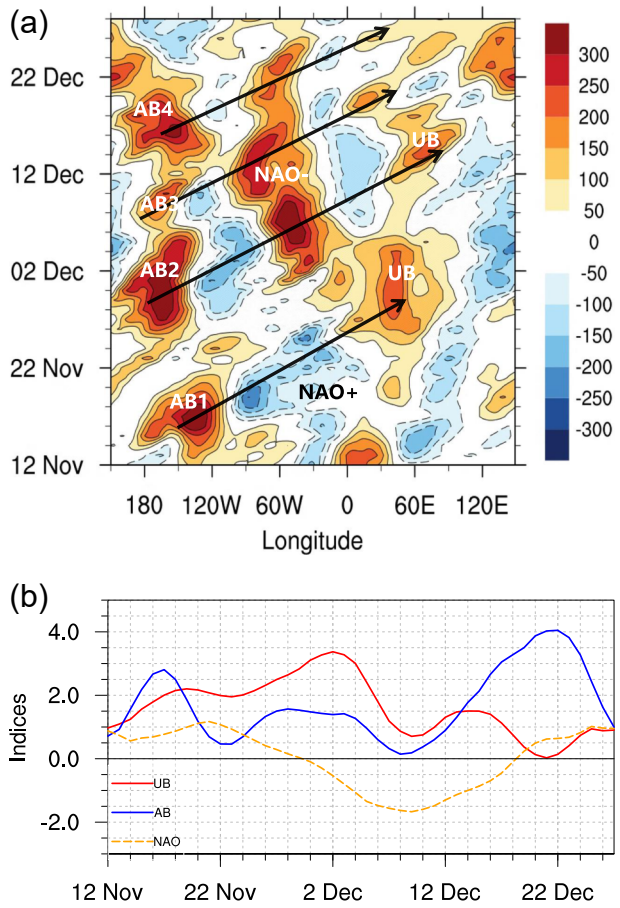


**Fig. 2.** (a) Hovmöller diagram of the daily 500-hPa geopotential height anomalies (shading and contour, units: gpm) averaged over 40°–70°N from 12 November to 27 December 2022. AB1 to AB4 represent four Alaska blocking events. Black lines with arrows indicate the propagation of Rossby wave packets. All the anomalies are calculated relative to the mean condition of 1979–2020. (b) Daily normalized indices of UB, AB, and NAO from 12 November to 27 December. The UB and AB indexes are based on dynamic tracking and regional averaging of the corresponding blocking anticyclonic centers.

UB in November is connected to the AB through the change of the NAO index from a positive to a negative value, as revealed by Luo et al. (2016b, 2018), from the energy dispersion perspective of a Rossby wave train.

In addition, we examined the signal throughout the troposphere and stratosphere. Figure 3 shows the regional mean geopotential height anomalies as a function of vertical levels from 6 November to 27 December. Figure 3a shows that in the Eurasian region, there is a downward-propagating stratospheric anomaly signal to the troposphere, as indicated by the black arrow. This process corresponded to the extreme snowstorm process in East Asia in late November and early December. A significant downward-propagating stratospheric signal in the North Pacific can also be observed from the middle through the end of December. The strong anticyclonic center in the troposphere is the blocking process that caused the "bomb cyclone" in North America. The downstream propagation of wave activity and the propagation between the stratosphere and troposphere can also be seen from the diagnosis of wave flux (Takaya and Nakamura, 2001), which is neither shown nor analyzed due to space limitation. In summary, frequent local blocking, Rossby wave packet propagation, NAO phase transition, and downward propagating stratospheric anomalies synergistically contribute to frequent extreme cold events during November–December.

The mean life span of a blocking event is about 5–8 days (Tibaldi and Molteni, 1990; Yao et al., 2017). However, in this November event, the UB lasted more than 20 days, while the AB lasted for nearly 20 days during December. Although

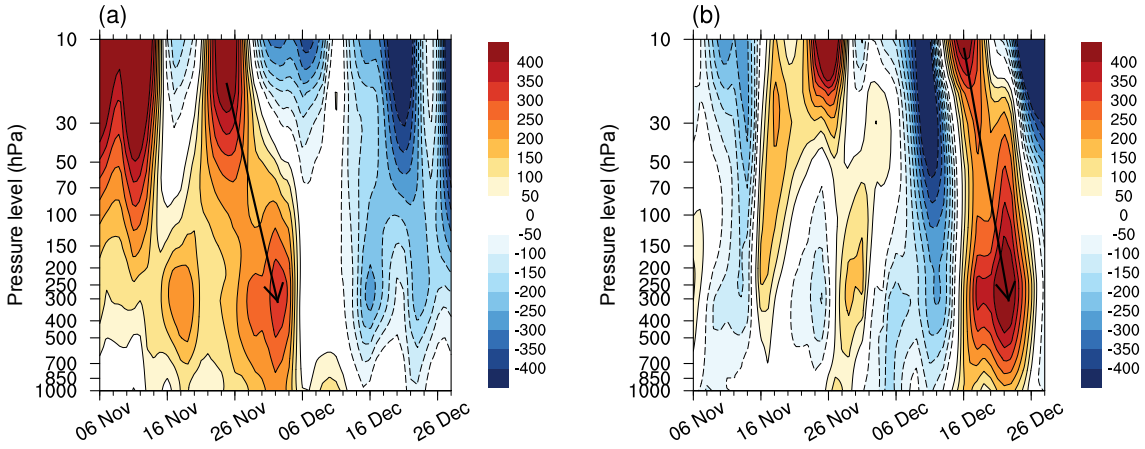


**Fig. 3.** The regionally averaged geopotential height anomalies (shading and contour, units: gpm) for (a) 0°–60°E, 60°–80°N and (b) 140°E–160°W, 60°–80°N as a function of vertical levels from 6 November to 27 December. Black lines with arrows indicate the downward propagation of a stratospheric anomaly signal. All the anomalies are calculated relative to the mean condition of 1979–2020.

the generation of a UB results from the dispersion and propagation of upstream wave trains associated with AB and NAO+ events, the persistent maintenance of a UB may be related to favorable background conditions.

### 3.3. *Physical background of extreme cold events from a $PV_y$ perspective*

Figure 4a shows the time mean distribution of the $PV_y$ anomalies from November to December 2022. Notably, $PV_y$ exhibits significant negative anomalies in mid-high latitudes from North America to Eurasia (Fig. 4a). Thus, the weak $PV_y$ in mid-latitudes is conducive to maintaining AB and UB events (Luo et al., 2019a). This explains why the AB and UB events lasted for about 20 days. Figure 4b further shows the variation of zonal mean $PV_y$ as a function of latitude for November–December in 2022. The averaged $PV_y$ for November to December 2022 (black line) is extremely low, with most mid-high latitudes (52°–70°N) below the lower quartile values from 1979–2022. In addition, the difference in composite $PV_y$ between La Niña and El Nino years is shown in Fig. 4c. It was found that La Niña years are favorable for the weakening of $PV_y$ in mid-latitudes (46° to 60°N, above the 90% confidence level around 50ºN). The same composite comparison is also applied to low SIC years (below –0.3 std) and high SIC years (above 0.3 std). The differences are mainly concentrated in mid-high latitudes (50°–70°N), and the $PV_y$ is small in low SIC years compared to high SIC years. This implies that both low SIC and La Niña events favor weak $PV_y$ in the mid-latitudes. However, the effect of low SIC on the reduction of mid-latitude $PV_y$ was not as profound as those of La Niña. The comparison between La Niña years with low SIC and El Niño years with high SIC (red line) shows that their combination (La Niña years with low SIC) benefits weaker $PV_y$ in mid-latitudes (above the 90% confidence level around 50ºN). This setting was consistent with the physical background of the frequent extreme cold events in November–December 2022 and with the synergistic effects of La Niña and Arctic SIC from the perspective of $PV_y$. Notably, our study can also explain why UB events differed in November and December. Although the mid-latitude $PV_y$ anomalies are weak in both November and December and favor UB events, the positive (negative) phase of NAO can promote (inhibit) the formation of a UB (Luo et al., 2016b). Thus, the NAO+ in November is favorable for the generation and maintenance of a downstream UB, but the NAO– in December suppresses the maintenance of UB. Consequently, there is a large difference in UB characteristics between November and December.

### 3.4. *Backward trajectories of water vapor for two key snowstorm processes*

Since North America and East Asia both suffered from disastrous snowstorms, it is necessary to analyze the source of water moisture during the two key snowfall processes. Figure 5 shows the distribution of 15-day backward moisture trajectories for the Great Lakes in the United States and Altay in Xinjiang China. The main moisture trajectories to the Great Lakes include the pathways from the Arctic Ocean, the Western Pacific, the Bering Strait, and scattered areas in western North America (Figs. 5a–c). The snowfall process lasted for three days, showing different water moisture pathways each day. On November 17 (Fig. 5a), the contribution ratio (shading) of water moisture trajectories from the Arctic Ocean was the highest, contributing more than 80% and even nearly 100% in some areas. The contribution ratio by the Arctic Ocean on November 18 (Fig. 5b) was still large, but parts of the Northwest Pacific had also made significant contributions. On November 19 (Fig. 5c), the contribution of moisture trajectories came mainly from the Bering strait and surrounding areas. In addition, the distribution of the moisture sources (Figs. S2a, c, and e in the ESM) displays a pattern with more local characteristics. In general, the greatest evaporation contribution comes locally, from the Great Lakes themselves, which have prominent evap-

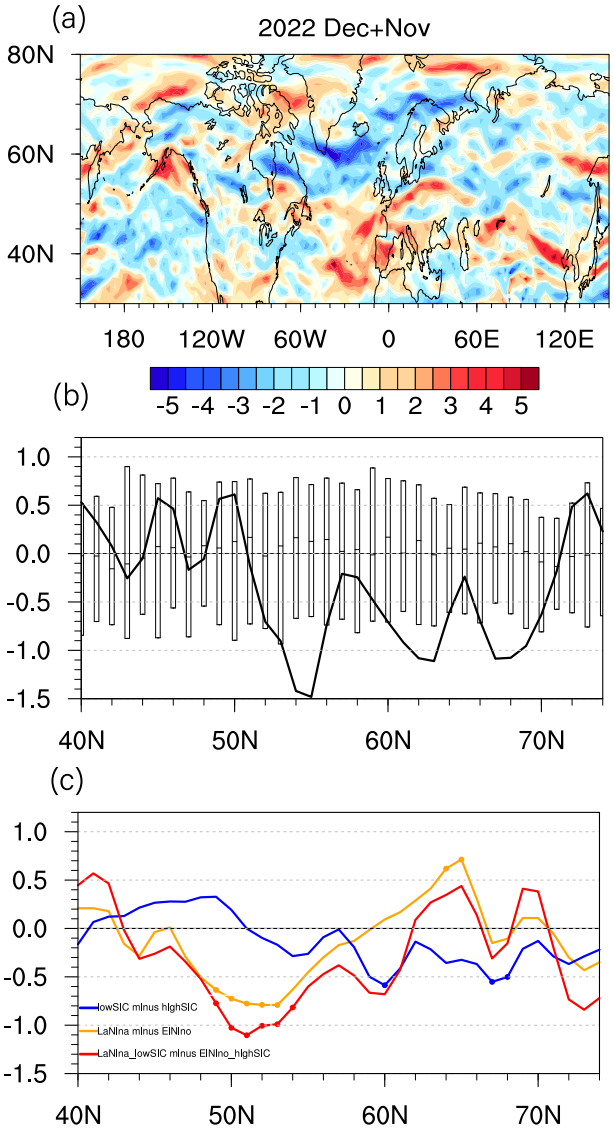


**Fig. 4.** (a) The monthly mean distribution of the nondimensional $PV_y$ anomalies for November and December 2022 (shading). (b) Zonal mean $PV_y$ anomalies as a function of latitudes for November–December, the black line represents 2022. The box plot indicates the dispersion of upper, median, and lower quartile values for $PV_y$ anomalies from 1979–2022. (c) Composite differences of $PV_y$ anomalies as a function of latitude. The blue line represents low SIC (23) years minus high SIC (21) years, the yellow line represents La Niña (18) years minus El Niño (14) years, and the red line represents La Niña (11) years with low SIC minus El Niño (6) years with high SIC. The dots represent latitudes above the 90% confidence level based on a two-tailed Student's t-test.

oration sources that are vital for its water vapor supply. The distributions of trajectories (Figs. S2b, d, and f) indicate that the Great Lakes are mainly influenced by the westerlies and their changes associated with an AB, as depicted in Fig. 1a.

Figures 5d–e show the distribution of 15-day backward moisture trajectories for Altay. The main moisture pathways to Altay are from the Arctic Ocean and the North Atlantic, associated with the branch of westerlies caused by Eurasian blocking. The contribution ratio (shading) of the Arctic was larger than the North Atlantic on 25 November, and on 26 November, the contribution ratio of the North Atlantic was even larger. The moisture contribution (Fig. S3a and c in the ESM) indicated that the contribution of water vapor to the snowfall in Altay and its surrounding areas mainly came from external sources.

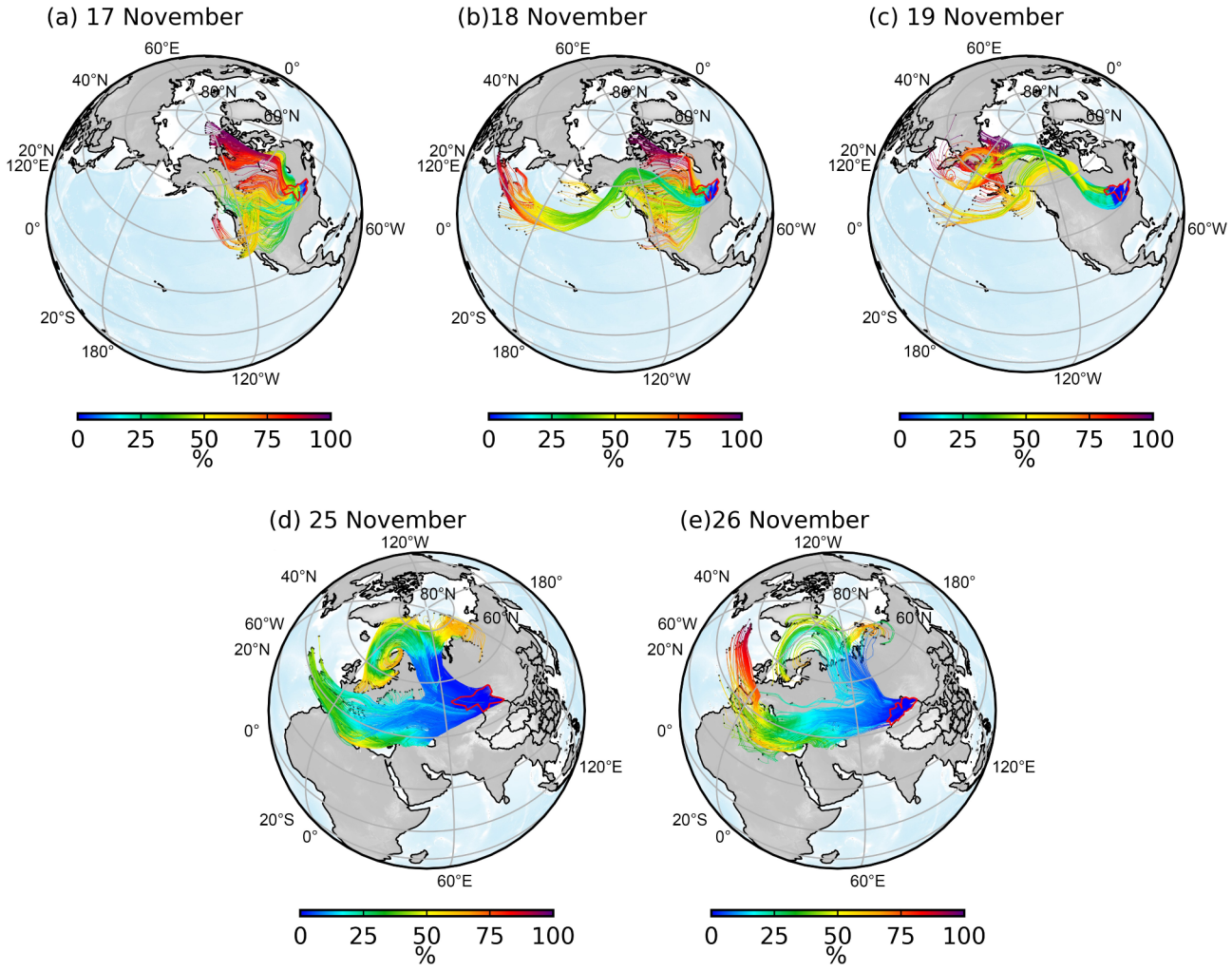


**Fig. 5.** The 15-day backward moisture trajectories for the Great Lakes on (a) 17 November, (b) 18 November, and (c) 19 November 2022, and for the Altay region on (d) 25 November and (e) 26 November 2022. The color of the trajectory indicates the accumulated moisture contribution ratio (units: %) from a given location on the trajectory to the origin of a backward trajectory (target region). The domains bounded by the red lines are the Great Lakes and the Altay regions.

The trajectory count distributions (Figs. S3b and d) suggest that the moisture pathway is closely associated with the change in the westerly jet caused by the blocking circulation.

## 4. Summary and discussion

Extreme cold events frequently occurred from North America to Eurasia in November and December 2022. The atmospheric circulation regime corresponding to each event was examined. Snowstorms in North America are associated with frequent AB, while cold extremes in East Asia are closely related to UB. It is found that the circulation regime that dominated the cooling process in East Asia starting on November 26 was a strong, extensive, and long-lived UB, which lasted for more than 20 days. In addition, the North American "bomb cyclone" around 25 December was associated with the combined effects of strong North Pacific blocking and a lower latitude AB ridge. In mid-December, the squeeze of the NAO– and the AB created two low-pressure cyclonic centers over North America, causing cooling and tornadic outbreaks.

Analysis based on a traditional Hovmöller diagram reveals that frequent propagation of Rossby wave packets occurred from the North Pacific to Eurasia in November and December 2022, implying a remote connection between these extreme events. The NAO+ in November contributed to the maintenance and strengthening of the UB, and the positive-to-negative transition of the NAO phase also supported the weakening of UB activity in December. The change in the Rossby wavenumber from two to three associated with the NAO phase transition is the main dynamic difference between November and December. Further, the two downward propagating stratospheric anomaly signals in East Asia and North America provide important energy supplements for the long-lived UB and AB events. The diagnosis of wave activity flux also corroborates these processes (figure not shown).

The $PV_y$ anomalies are negative in mid-high latitudes in November and December 2022, which are favorable conditions for the formation of AB and UB events, as well as for their longevity, even though UB is significantly influenced by upstream wave trains associated with AB events and the NAO phase. Further composites based on long-term climate series imply that both La Niña and low SIC conditions favor the formation of weak $PV_y$ at mid-latitudes. The combination of La Niña and low SIC conditions can further favor the weakening of mid-latitude $PV_y$, which is an important reason for the frequent extreme cold in November–December 2022. The $PV_y$ based on the NMI model used in this paper provides a unique perspective for understanding the physical processes of extreme cold events. If a small $PV_y$ continues in January–February 2023, it is expected that longer-lived UB events can frequently occur and lead to frequent severe cold extremes in late winter.

In addition, the moisture pathway of the two key snowstorm processes is closely related to the wave guidance and transport of westerlies. For the snowstorm near the Great Lakes, the local water vapor transport of the five Great Lakes plays the most important role. The water moisture pathways of Altay snowstorm came mainly from the North Atlantic and the Arctic Ocean, implying that the moisture source of this snowfall is mainly the contribution of external water vapor, and the contribution of local water vapor is small.

By focusing on the frequent extreme cold events of November to December 2022, we reveal the possible influence of AB and UB events and their connection under the background of La Niña and SIC from the perspective of $PV_y$. However, many other factors which affect extreme weather and climate need further examination, including those related to observation, modeling results, and theory.

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