

LETTER • OPEN ACCESS

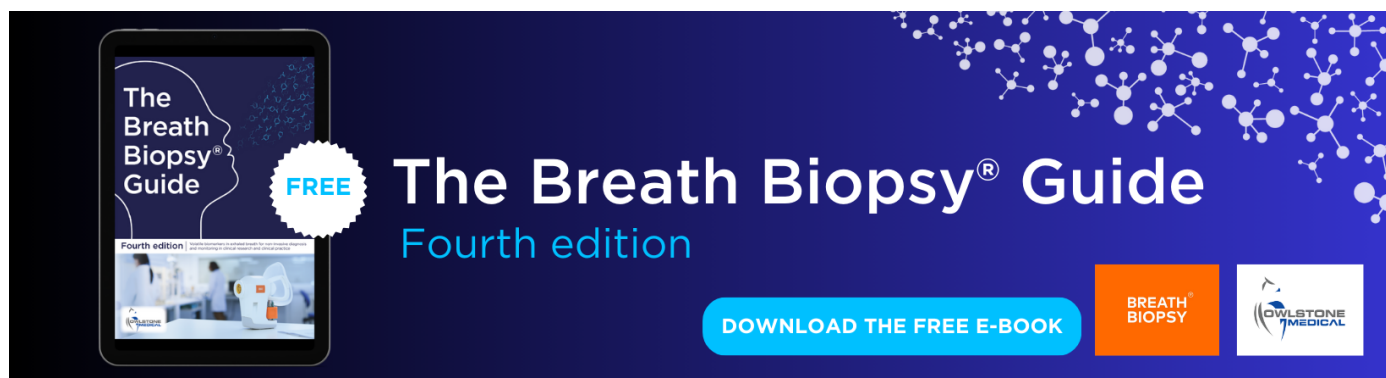
ENSO and QBO modulation of the relationship between Arctic sea ice loss and Eurasian winter climate

To cite this article: Xuan Ma *et al* 2022 *Environ. Res. Lett.* **17** 124016

View the [article online](#) for updates and enhancements.

You may also like

- [Longitudinally Asymmetric Stratospheric Oscillation on a Tidally Locked Exoplanet](#)
Maureen Cohen, Massimo A. Bollasina, Paul I. Palmer *et al.*
- [Causal Interaction between the Subsurface Rotation Rate Residuals and Radial Magnetic Field in Different Timescales](#)
Fadil Inceoglu, Rachel Howe and Paul T. M. Loto'aniu
- [Helioseismic Investigation of Quasi-biennial Oscillation Source Regions](#)
Kiran Jain, Partha Chowdhury and Sushanta C. Tripathy



The Breath Biopsy® Guide
Fourth edition

FREE

DOWNLOAD THE FREE E-BOOK

BREATH BIOPSY

OWLSTONE MEDICAL

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

OPEN ACCESS

RECEIVED
17 July 2022REVISED
7 November 2022ACCEPTED FOR PUBLICATION
22 November 2022PUBLISHED
15 December 2022

Original content from
this work may be used
under the terms of the
[Creative Commons
Attribution 4.0 licence](#).

Any further distribution
of this work must
maintain attribution to
the author(s) and the title
of the work, journal
citation and DOI.



ENSO and QBO modulation of the relationship between Arctic sea ice loss and Eurasian winter climate

Xuan Ma¹ , Lei Wang^{1,2,3,*} , Doug Smith⁴ , Leon Hermanson⁴ , Rosie Eade⁴ , Nick Dunstone⁴ , Steven Hardiman⁴ and Jiankai Zhang^{5,6} ¹ Department of Atmospheric and Oceanic Sciences & Institute of Atmospheric Sciences, Fudan University, Shanghai, People's Republic of China² Innovation Center of Ocean and Atmosphere System, Zhuhai Fudan Innovation Research Institute, Zhuhai, People's Republic of China³ Shanghai Qi Zhi Institute, Shanghai, People's Republic of China⁴ Met Office Hadley Centre, Fitz Roy Road, Exeter, United Kingdom⁵ College of Atmospheric Sciences, Lanzhou University, Lanzhou, People's Republic of China⁶ Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, People's Republic of China

* Author to whom any correspondence should be addressed.

E-mail: wanglei_ias@fudan.edu.cn**Keywords:** Barents–Kara Sea sea ice, Eurasian winter climate, ENSO, QBO, stratosphere–troposphere couplingSupplementary material for this article is available [online](#)

Abstract

The causality between Arctic sea ice decline and cold boreal winters has been widely debated recently and remains controversial. A major source of uncertainty in the sea ice–cold winter relationship originates from that the stratosphere polar vortex (SPV) is not only affected by Arctic sea ice anomaly but can also be modulated by El Niño–Southern Oscillation (ENSO) and quasi-biennial oscillation (QBO). Using reanalysis data and hindcasts from the decadal prediction system version 4, here we show that both cold and warm winters occur over Eurasia when the Barents–Kara Sea sea ice is abnormally low. Warm winters occur during the La Niña–easterly QBO–low sea ice (LANINA–EQBO–LICE) years and cold winters during the neutral ENSO–neutral QBO (NENSO–NQBO)–LICE and El Niño (ELNINO)–NQBO–LICE years. During the LANINA–EQBO–LICE years, weakened upward-propagating planetary waves from the troposphere to the stratosphere strengthen the Arctic SPV and then weaken the Aleutian low and Siberian high, creating conditions favorable for Eurasian warming. The atmospheric responses are opposite in the NENSO–NQBO–LICE and ELNINO–NQBO–LICE years. This implies that care should be taken in using Arctic sea ice alone as the precursor to predict boreal winter climate.

1. Introduction

During the past few decades, several extremely cold winters occurred in Eurasia despite global warming (Coumou and Rahmstorf 2012, Liu *et al* 2012, Cohen *et al* 2020, Bailey *et al* 2021, Cohen *et al* 2021, Zheng *et al* 2022), which had imposed severe threats to electrical power transmission, energy supply, agriculture, air pollution, and even human lives (Kamo *et al* 2016, Wang *et al* 2016, Thornton *et al* 2017, Lu *et al* 2022). Therefore, a better understanding of the precursors and related potential mechanism for cold winters is of great importance for human life and societal development.

Some observational and modeling studies attributed these cold winters to the rapid decline of Arctic sea ice in autumn or winter, especially over the Barents–Kara Sea (BKS) (Liu *et al* 2012, Tang *et al* 2013, Wu *et al* 2013, Mori *et al* 2014, Xu *et al* 2021). Using the atmospheric general circulation model, Zhang *et al* (2018b) proposed a dynamical mechanism explaining the relationship between the Arctic sea ice and midlatitude circulation based mainly on the stratospheric pathway rather than the tropospheric pathway. The enhanced upward planetary wave induced by sea ice loss could propagate into the stratosphere, and thus weaken the stratospheric polar vortex (SPV) (Jaiser *et al* 2013, Kim *et al* 2014, Peings

and Magnúsdóttir 2014, Nakamura et al 2016, Hoshi et al 2017, Zhang et al 2018a). These stratospheric circulation anomalies forced by Arctic sea ice can persist for a couple of months and subsequently propagate downward to the midlatitude surface, resulting in cooling over most parts of northern Eurasia (Kim et al 2014, Peings and Magnúsdóttir 2014, Sun et al 2015, Zhang et al 2018b). Moreover, the BKS sea ice reduction could also contribute to the SPV shift, leading to a colder climate over some parts of the Eurasian continent (Zhang et al 2016). These studies imply that the SPV can act as a bridge linking the BKS sea ice and midlatitude climate.

Recently, some studies have discussed the lagged impact of the Arctic sea ice (e.g. Liu et al 2019, Ding et al 2021, Yang et al 2022). For example, Yang et al (2022) pointed out that the long-lagged impact of the Arctic sea ice in BKSs on June precipitation in eastern China can be interpreted by the long memory of the sea ice concentration, polar vortex, and the downward propagation of stratospheric anomalies. However, the response of mid-to-high latitude weather and climate to the changes in Arctic sea ice is still subject to great uncertainty (Screen et al 2014, Overland et al 2015, Perlwitz et al 2015, Semenov and Latif 2015, Wu et al 2015, Overland et al 2016, Wu 2018). For example, the winter of 2006/2007 was extremely warm, while the corresponding Arctic sea ice in early September was abnormally low (Li et al 2011, Wu et al 2011). Ayarzagüena and Screen (2016) demonstrated that Arctic sea ice loss is also accompanied by a reduction in the *strength* of cold-air outbreaks in the midlatitudes. Further, numerous modeling studies tried to separate the impact of sea ice and atmospheric internal variability on Eurasian cooling. Based on atmosphere-only and coupled atmosphere–ocean simulations, they have shown that cold Eurasian winters are attributed to atmospheric internal variability, rather than a change in sea ice forcing (McCusker et al 2016, Sun et al 2016, Collin et al 2018), indicating that external forcings only contribute to the chance of cold winters appearing with a higher probability density function. In addition, some studies indicate that the link between Arctic sea ice and midlatitude weather and climate can be modulated by tropical processes (Baxter et al 2019, Warner et al 2019).

Since the stratospheric pathway appears to be an important link between the BKS sea ice and midlatitude climate, we envision that the uncertainty of stratospheric process may be responsible for the nonstationary relationship between sea ice loss and cold winters. SPV is an essential system linking the Arctic stratosphere and troposphere. Studies have shown that the SPV can be largely modulated by El Niño–Southern Oscillation (ENSO) and quasi-biennial oscillation (QBO) besides Arctic sea ice (Ren et al 2012, Calvo et al 2017, Ren et al 2017,

Zhou et al 2018, Zhang et al 2020, Rao et al 2021, Kumar et al 2022). Garfinkel et al (2010) showed that QBO and Aleutian low associated with ENSO can explain $\sim 39.6\%$ of polar vortex variability during winter in the reanalysis record. Specifically, during the El Niño (ELNINO) years, the associated Pacific North America pattern is accompanied by an intensified Aleutian low-pressure system, which subsequently increases the upward planetary wave and weakens the SPV before reflecting back to the surface (Ineson and Scaife 2009). As expected from dynamical considerations, Domeisen et al (2019) demonstrated that the ELNINO years are often linked with a strengthened Brewer–Dobson circulation and thus lead to a warming of the polar regions through adiabatic warming. The circulation responses are often opposite in the La Niña (LANINA) years (Free and Seidel 2009, Mitchell et al 2011, Domeisen et al 2019). As for the QBO, Holton and Tan (1980) found that the wintertime SPV is stronger in the westerly QBO (WQBO) phases than in the easterly QBO (EQBO), which is confirmed by numerical simulations (Zhang et al 2019, Rao et al 2020, Elsbury et al 2021) and observations (Lu et al 2020, Yamazaki et al 2020). Using the Coupled Model Intercomparison Project (CMIP) models, Richter et al (2020) found that the number of models that are able to simulate the QBO has increased from CMIP5 to CMIP6. This motivates us to explore the role of ENSO and QBO in the Eurasian surface air temperature (SAT) affected by BKS sea ice through stratospheric processes.

The goal of this work is to consider whether ENSO and QBO interfere with links between the BKS sea ice loss and Eurasian winter climate. Section 2 introduces the data and models used in this study. The responses of Eurasian wintertime SAT forced by sea ice (ICE), ENSO, and QBO, and the possible mechanisms are shown in section 3. Summary and conclusions are presented in section 4.

2. Model, observational data, and methods

2.1. Model

The model utilized in this study is the decadal prediction system version 4 (DePreSys4) developed and deployed at the United Kingdom Met Office. This system produced the first initialized short-term climate prediction in 2007 (Smith et al 2007) but now uses the Hadley Centre Global Environmental Model version 3 as described in Dunstone et al (2016). Natural variability and human influences are simulated in this system using CMIP6 forcing datasets and it consists of four components: atmosphere, ocean, land, and cryosphere (land ice and sea ice). The horizontal resolution of atmosphere data used in this paper is 0.556 degrees of latitude by 0.833 degrees of longitude with 36 levels extending from

the surface to 0.03 hPa. DePreSys4 hindcast consists of ten ensemble members each starting from different ocean analyses sample uncertainties in the initial conditions. The DePreSys4 hindcasts start each November from 1960 to 2019 and run for 10 years and 4 months.

2.2. Observational data and index definitions

Atmospheric data (monthly mean zonal wind and SAT) from the Japanese 55 year Reanalysis Project (JRA-55) are employed with a horizontal resolution of $1.25^\circ \times 1.25^\circ$ (Kobayashi *et al* 2015). The monthly sea ice and sea surface temperature (SST) data are from the UK Met Office Hadley Centre with a spatial resolution of $1.0^\circ \times 1.0^\circ$ (Rayner *et al* 2003). We also employ another monthly sea ice dataset from the National Snow and Ice Data Center (Meier *et al* 2014) for comparison.

Several indices are used in this paper. Sea ice extent (SIE) index is defined as the total marine area in which the ice concentration is at least 15% over the BKS region (70°N – 82°N , 20°E – 90°E). The strength of the SPV is defined as the zonal wind at 60°N and 10 hPa (Hardiman *et al* 2020). Strong and weak SPV winters with low SIE (the normalized SIE less than -0.5) are selected based on the threshold of ± 0.5 standard deviation of the SPV strength index. According to this criterion, observed weak SPV/low SIE winters are 1965/1966, 1972/1973, 1984/1985, 2000/2001, 2012/2013, and 2018/2019, whereas strong SPV/low SIE winters are 1961/1962, 1983/1984, 1985/1986, and 1995/1996. As previous studies (Holton and Tan 1980, Son *et al* 2017, Zhang *et al* 2019), the QBO index is calculated by zonal mean zonal wind at 50 hPa averaged over 10°S – 10°N . The Niño 3.4 index, which is the area-averaged SST over 5°S – 5°N and 170°W – 120°W , is used to represent the ENSO signal. Following Gong *et al* (2001), the regional averaged sea level pressure in the midlatitudes of East Asia (40°N – 60°N , 70°E – 120°E) is used to represent the intensity of Siberian high. As presented in Wang and He (2012), the sea level pressure averaged in the region of 155°E – 130°W and 30°N – 70°N is defined as the strength of Aleutian low.

Composite analysis is the main method utilized in this paper. To obtain more samples for each composite, we superimposed the atmospheric response of opposite phases of ENSO and QBO, assuming that the atmospheric response to opposite ENSO and QBO phases can be offset. For example, the summation of the results of ENSO in positive and negative phases is considered as that for neutral ENSO (NENSO), and the summation of QBO in positive and negative phase is considered as neutral QBO (NQBO). In addition, the weights used for the summation are defined according to their polar vortex strengths, i.e. they

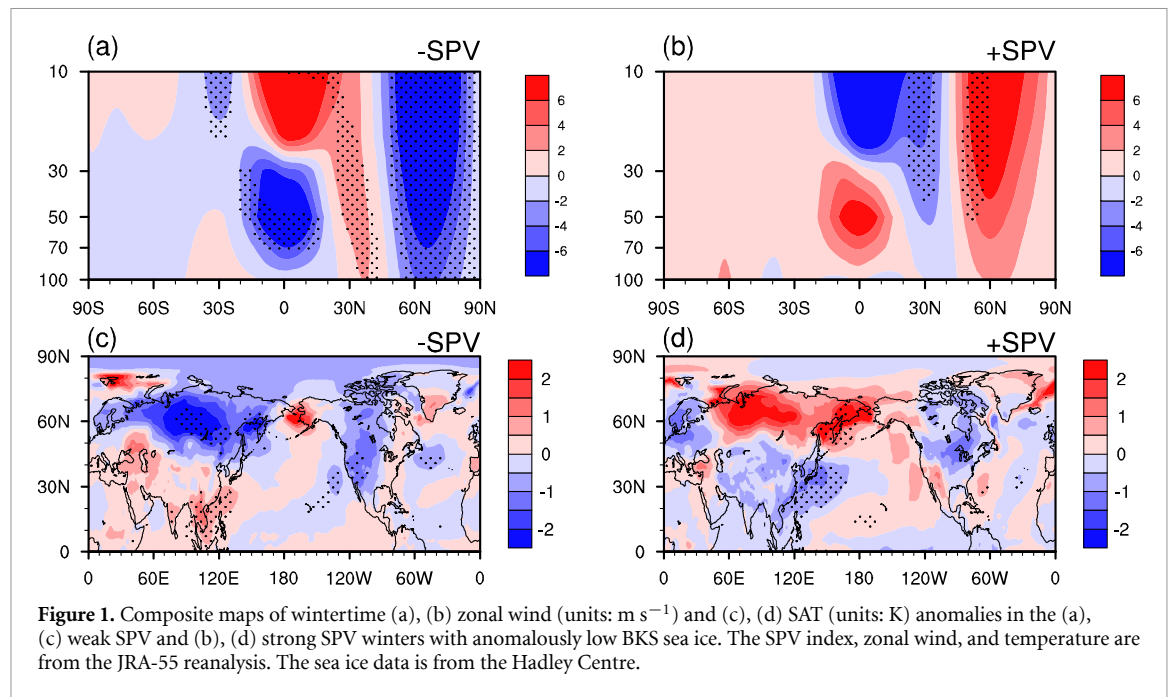
are weighted by polar vortex strengths during 1960–2019. Taking QBO as an example, α is the ratio of the pole vortex intensity in the EQBO years to that in the WQBO years. The atmospheric response during the WQBO years is multiplied by α and then adds the atmospheric response during the EQBO years to offset the atmospheric response of QBO as much as possible, which is considered as the result of NQBO. Analogously, in this way, the LANINA-NQBO-LICE events and the ELNINO-NQBO-LICE events are included to increase the number of NENSO-NQBO-LICE events, and the NENSO-WQBO-LICE and NENSO-EQBO-LICE events are included to increase the number of NENSO-NQBO-LICE events.

3. Results

Figure 1 shows the subsequent zonal mean zonal wind and temperature in winter when the preceding autumn BKS sea ice is anomalously low based on the observational record. Under low BKS sea ice conditions, Eurasian winter SAT is abnormally cold when the SPV is weak and is abnormally warm when the SPV is strong. This indicates that if the link between Arctic sea ice and Eurasian SAT is through the SPV then it can be masked by other variability, which motivates us to investigate the role of ENSO and QBO due to their strong connections with SPV variability.

Time series of autumn SIE and wintertime ENSO and QBO indexes and their lead-lag correlation are presented in figure S1. Consistent with previous studies, a clear downward trend is found in the autumn SIE index (e.g. Chen *et al* 2021, Docquier and Koenigk 2021, Yang *et al* 2022), while no significant trend can be seen in ENSO and QBO. All three factors exhibit significant interannual variability. Garfinkel *et al* (2010) pointed out that the effects of ENSO and QBO on the polar vortex were independent of each other. The lead-lag correlation between autumn SIE and wintertime ENSO and QBO presented in figure S1(b) also indicates that the ENSO and QBO are not correlated with autumn SIE during 1960–2019.

Since only a few observed events can be found in each combination of ENSO and QBO phases under low BKS SIE conditions from the observational record, the DePreSys4 hindcasts with ten ensemble members are used to minimize the impact of internal variability in this paper. All ensemble members can well reproduce the observed Northern Hemisphere SAT climatological spatial distribution with all correlation coefficients above 0.99 and relative amplitude close to 1.0 (figure S2). Previously, Andrews *et al* (2019, 2020) pointed out that this model has a good performance in reproducing the QBO and Arctic sea ice. In addition, simulated QBO-Arctic Oscillation teleconnections are similar to that shown in



observations (Andrews *et al* 2019) and we have also presented its good ability in performing the tropospheric responses to Arctic sea ice.

It is necessary to investigate the relationship between the Arctic stratospheric circulation and ENSO, QBO, and ICE beforehand, as shown in figure 2. The Arctic polar vortex is negatively linearly related to ENSO, positively linearly related to QBO, and nonlinearly related to ICE. Previously, some studies pointed out the asymmetry and the non-linearity of the influences of ENSO on the northern winter stratosphere (Rao and Ren 2016a, 2016b). In this study, we discuss the role of ENSO on the premise of low Arctic sea ice, and in this situation, the non-linearity of ENSO is relatively weaker. To explore the potential mechanism underlying the nonstationary relationship between BKS sea ice and Eurasian SAT, the wintertime zonal wind responses for all combinations are shown in figure 3. In the case of low sea ice (LICE) in the BKS, three combinations are investigated, and they show a significant downward propagation of the stratospheric circulation anomalies forced by ENSO, QBO, and ICE (figures 4 and S3) and the polar vortex anomalies of the other combinations are too weak or cannot propagate significantly to the surface (figure S3). The total occurrence of the three combinations is 25% under low BKS SIE conditions. Specifically, the occurrence is 12.5% for the first combination (LANINA-EQBO-LICE) and 6.25% for the latter two combinations. The Arctic SPV appears to be stronger during the LANINA-EQBO-LICE years (figure 4(a)), and weaker during the NENSO-NQBO-LICE and ELNINO-NQBO-LICE years (figures 4(b) and (c)). The enhanced SPV in figure 4(a) may be mainly attributed to the LANINA since EQBO and

LICE favor a weakening of the polar vortex and the weakened SPV in figure 4(b) is primarily a result of the reduction of BKS sea ice, as ENSO and QBO are in the neutral states. While the weakened SPV illustrated in figure 4(c) is ascribed to the joint effect of ELNINO and the reduction of BKS sea ice, as QBO is in the neutral state. In the case of high BKS sea ice, almost opposite responses are observed (figure S4). Thus, only LICE conditions are discussed in this paper.

Previous studies have shown that the Arctic SPV changes forced by ENSO, QBO, and ICE are largely caused by dynamical processes (planetary waves activity) (e.g. Garfinkel *et al* 2010, Zhang *et al* 2016, 2018b). The responses of Eliassen–Palm (EP) fluxes for the three combinations are thus depicted in figure 5. The planetary wave activity is weakened in the LANINA-EQBO-LICE years (figures 5(a) and (d)), indicating that LANINA events strengthen the Arctic SPV by suppressing upward planetary wave activity. Consistent with previous studies, the BKS sea ice loss in autumn could excite anomalous upward planetary waves and weaken the SPV (figures 5(b) and (e)). Changes in upward planetary waves in the ELNINO-NQBO-LICE years (figures 5(c) and (f)) are also enhanced as in the NENSO-NQBO-LICE years, which eventually leads to a weakened SPV. Figure S5 shows the longitude-latitude maps of wavenumbers 1 and 2 of zonal wind composites at 10 hPa. The weakened SPV in the NENSO-NQBO-LICE and ELNINO-NQBO-LICE years (figures 4(b) and (c)) is attributable to the enhanced vertically propagating stationary waves-1 and 2. Conversely, the stronger SPV during the LANINA-EQBO-LICE (figure 4(a)) years is dominated by reduced upward

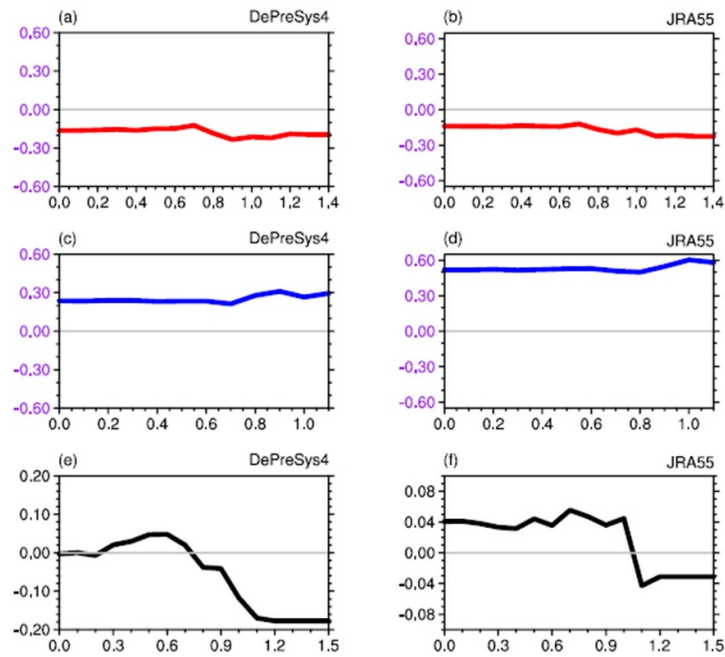


Figure 2. (a) Amplitude dependence of the regression of the averaged polar stratospheric zonal wind (50° N– 90° N and 10–50 hPa) onto the Niño 3.4 index using the DePreSys4 ensemble mean hindcasts. The x-axis indicates the threshold of Niño 3.4 index and only the years with the Niño 3.4 index exceeding the x-axis are chosen to calculate the regression coefficients. Note that thresholds with too few events leading to unreasonably large regression coefficients are not included. All the time series are standardized and the QBO and sea ice signals are linearly regressed out before calculating the regression coefficients. (c) and (e) Same as (a), but for QBO and BKS sea ice, respectively. (b), (d), (f) Same as (a), (c), (e), but for JRA55. All calculations are based on the monthly mean data.

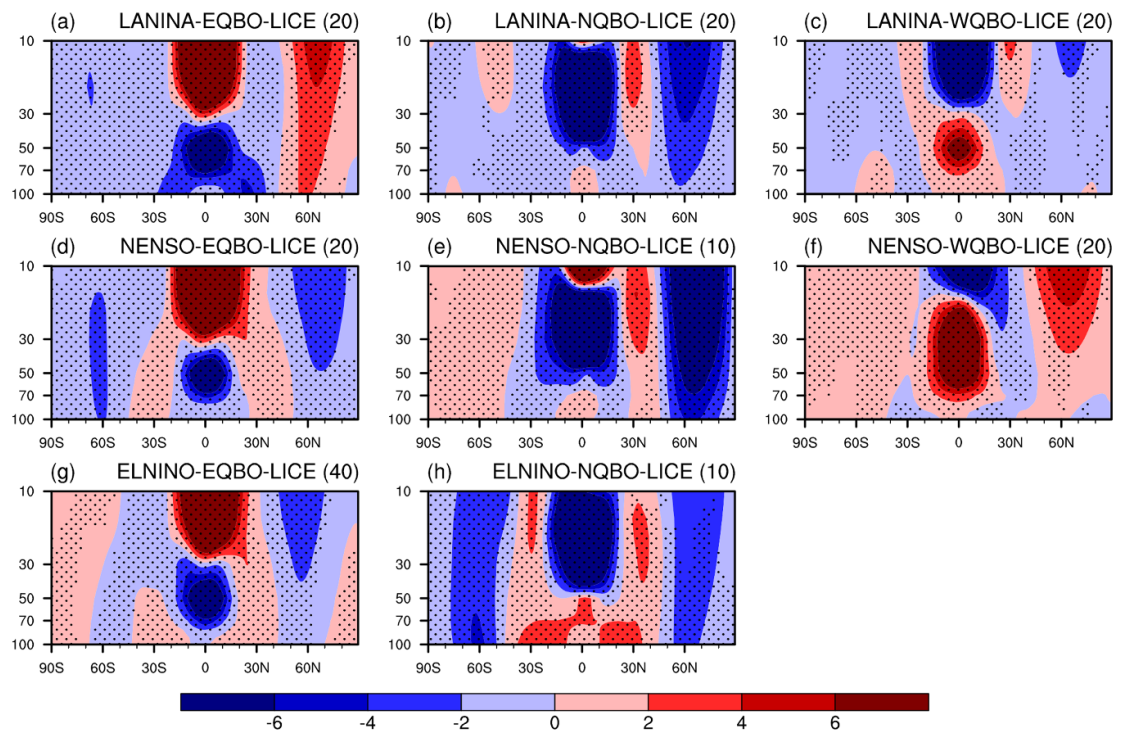
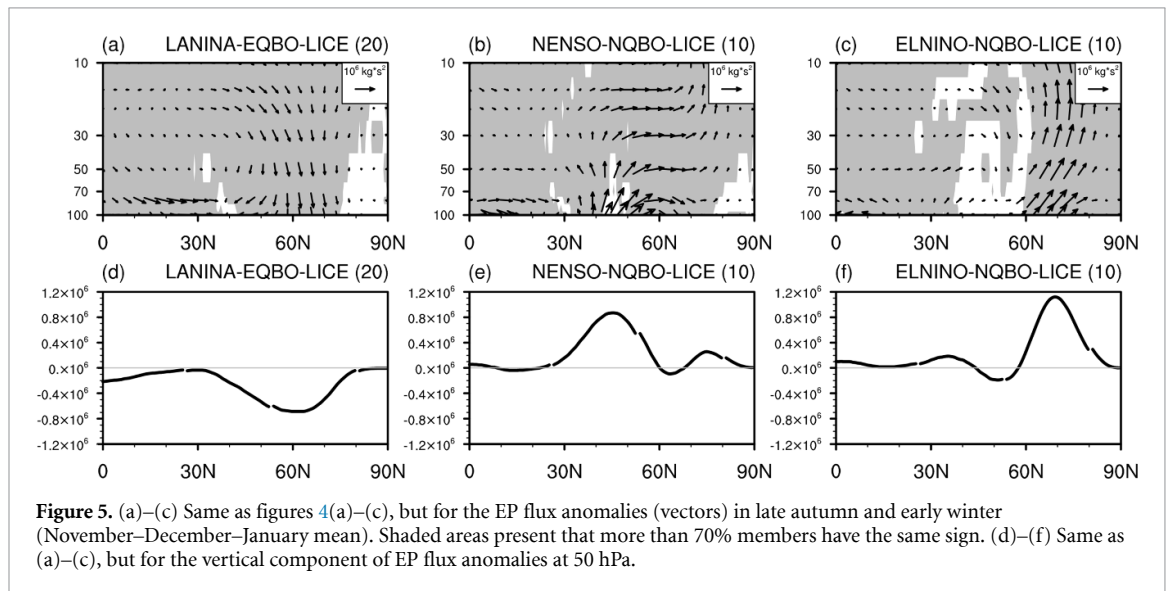
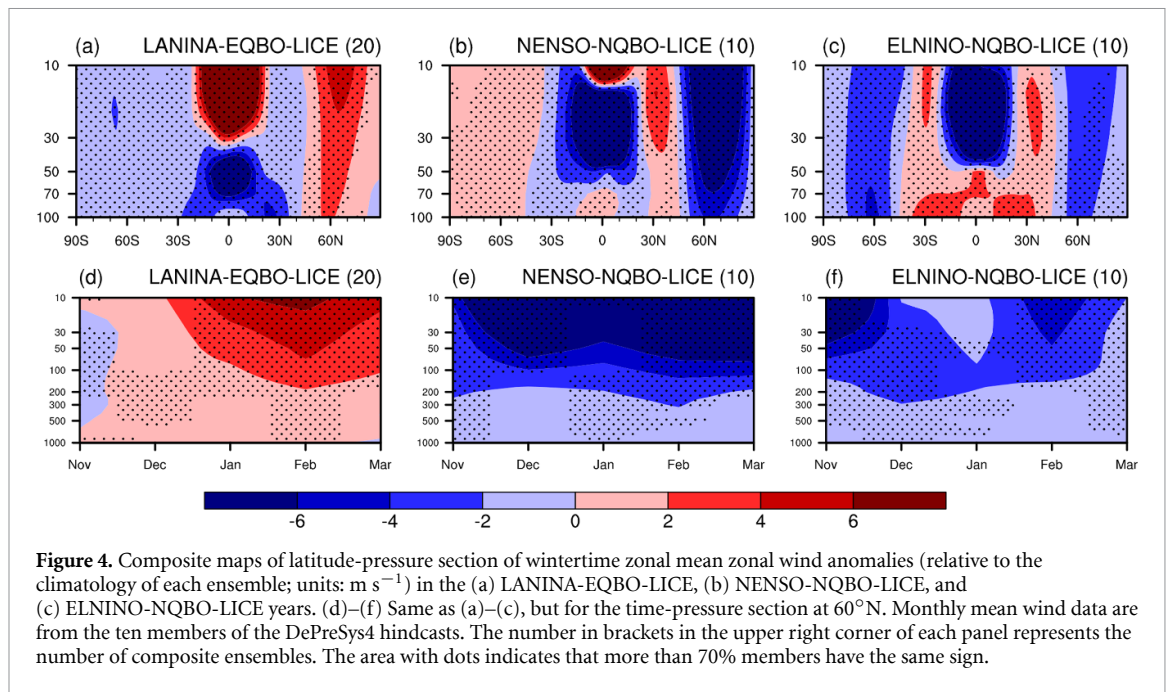


Figure 3. Composite maps of latitude-pressure section of wintertime zonal mean zonal wind anomalies (relative to the climatology of each ensemble; units: m s^{-1}) for the eight combinations (no ELNINO-WQBO-LICE events occur). Monthly mean wind data are from the ten members of the DePreSys4 hindcasts. The number in brackets in the upper right corner of each panel represents the number of composite ensembles. The area with dots indicates that more than 70% members have the same sign.

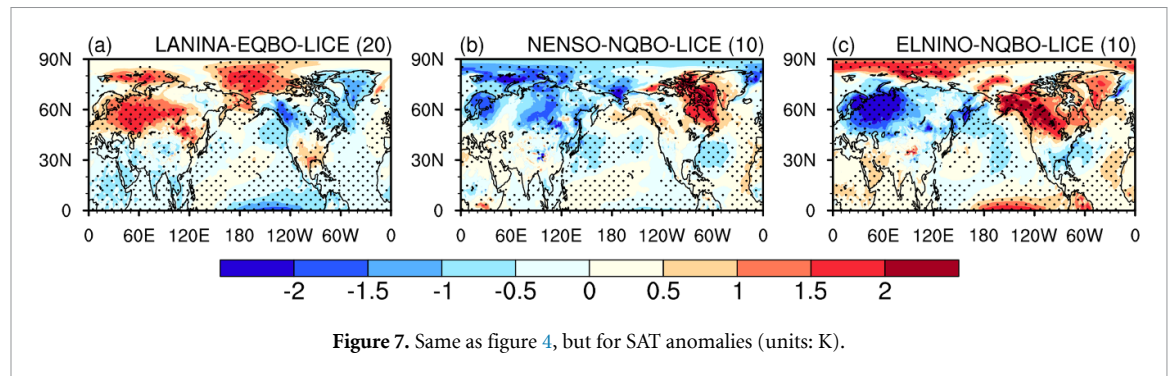
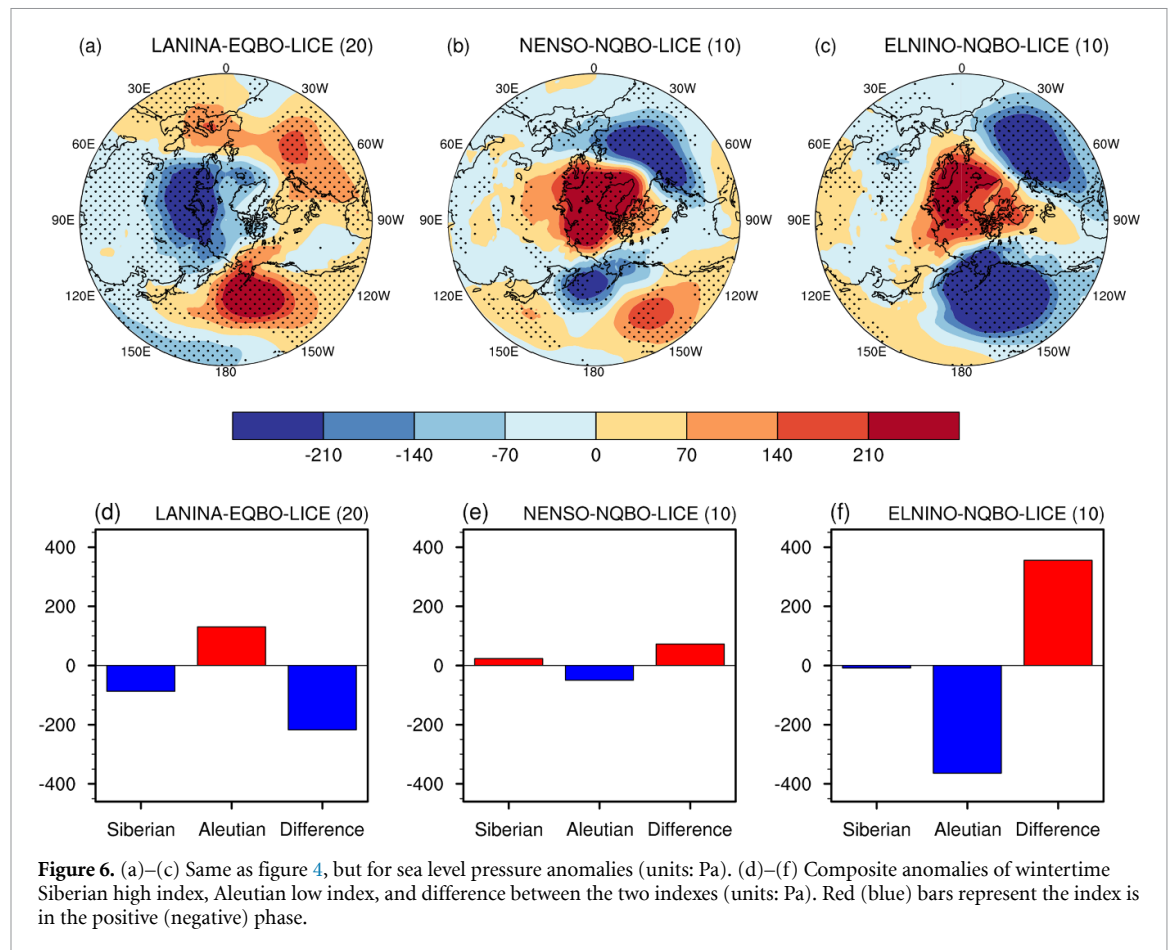


propagating stationary wave of wavenumber-2 and possibly changes in the transient waves.

Studies have shown that stratospheric circulation anomalies are closely related to the East Asian winter monsoon (EAWM) (Ma et al 2021, Lu et al 2022), which is one of the main factors in driving wintertime SAT variations over many regions of Eurasia (Chen et al 2005, Sung et al 2010). We further investigate the tropospheric responses to the stratospheric circulation anomalies. A positive North Atlantic Oscillation (NAO) signal appears during the LANINA-EQBO-LICE years (figure 6(a)), while opposite circulation responses are displayed in the latter two combinations with negative NAO signals over the North Atlantic sector (figures 6(b) and (c)). Usually, cold Eurasian winters coincide with a negative NAO and warm winters with a positive NAO. This suggests that the

circulation changes shown in the first combination are favorable for Eurasian warming, while the circulation changes shown in the latter two combinations are in favor of Eurasian cooling (Hirschi and Sinha 2007, Xie et al 2019). In addition, Miao and Wang (2020) pointed out that Siberian high and Aleutian low are two important components of the EAWM system. As displayed in figure 6(a), during the LANINA-EQBO-LICE years, weakened Siberian high and Aleutian low indicate that it is conducive to Eurasian warming with this anomalous circulation (figure 6(d)). Opposite responses are found in the latter two combinations (figures 6(e) and (f)).

The responses of Northern Hemisphere wintertime SAT for the three combinations are shown in figure 7 (see figure S6 for all eight combinations). The temperature anomalies are characterized



by warm Eurasia pattern during the LANINA-EQBO-LICE years (figure 7(a)) and cold Eurasia pattern during the NENSO-NQBO-LICE (figure 7(b)) and ELNINO-NQBO-LICE years (figure 7(c)). Mori *et al* (2014) argued that the warm Arctic-cold Eurasia pattern is a direct atmospheric response to the decline of the BKS sea ice, which is consistent with our results shown in parts of Eurasia in figure 7(b). The cold Eurasia shown in figure 7(c) is the results of ELNINO superimposed on the LICE (in contrast to the LICE-only forcing in figure 7(b)). These Eurasian SAT anomalies are consistent with the changes in Arctic SPV and surface circulation related to the three combinations.

4. Conclusions

This study provides observational and modeling evidence that the BKS sea ice reduction does not always lead to a cold Eurasian winter. Using reanalysis and DePreSys4 hindcasts, we evaluated the role of ENSO and QBO in modulating the linkage between autumn BKS sea ice and winter Eurasian SAT. Results show that the stratospheric polar vortex, as a bridge linking BKS sea ice and Eurasian winter climate, can be significantly influenced by ENSO and QBO. Both cold and warm Eurasian winters can occur when BKS sea ice is abnormally low. Specifically, SAT anomalies show a warm Eurasia pattern during

the LANINA-EQBO-LICE years and a cold Eurasia pattern during the NENSO-NQBO-LICE and ELNINO-NQBO-LICE years. The physical processes responsible for the modulation by ENSO and QBO on the ICE-SAT relationship can be attributable to the SPV changes associated with ENSO, QBO, and ICE. During the LANINA-EQBO-LICE years, the polar vortex is strengthened by suppressed upward planetary wave activity and couples downward with the tropospheric circulation, leading to a positive NAO, weaker Siberian high and Aleutian low in winter. These conditions are conducive to warm Eurasian winters. Opposite responses of the stratospheric and tropospheric circulation are found during the NENSO-NQBO-LICE and ELNINO-NQBO-LICE years, leading to cold Eurasian winters.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

Funding for this project was provided by the National Natural Science Foundation of China (Grant 41875047), the National Key Research and Development Program of China under Grant 2019YFA0607000 (2019YFA0607002), and Postdoctoral Innovative Talent Support Program of China (BX20220039). Dr Jiankai Zhang was supported by the Fundamental Research Funds for the Central Universities (lzujbky-2021-ey04). We thank the Met Office for providing the DePreSys4 hindcasts data. We also acknowledge UK Met Office Hadley Centre for providing the SST data (www.metoffice.gov.uk/hadobs/hadisst/), NSIDC for sea ice data (<https://nsidc.org/data/NSIDC-0079/versions/3>), and Japanese Meteorological Agency for other Meteorological fields from JRA-55 (<https://rda.ucar.edu/>).

ORCID iDs

Xuan Ma  <https://orcid.org/0000-0002-0596-0786>
 Lei Wang  <https://orcid.org/0000-0002-1618-1796>
 Doug Smith  <https://orcid.org/0000-0001-5708-694X>
 Leon Hermanson  <https://orcid.org/0000-0002-1062-6731>
 Rosie Eade  <https://orcid.org/0000-0002-3566-4232>
 Nick Dunstone  <https://orcid.org/0000-0001-6859-6814>
 Steven Hardiman  <https://orcid.org/0000-0001-9813-1209>
 Jiankai Zhang  <https://orcid.org/0000-0002-8491-0225>

References

- Andrews M B *et al* 2020 Historical simulations with HadGEM3-GC3.1 for CMIP6 *J. Adv. Model. Earth Syst.* **12** e2019MS001995
- Andrews M B, Knight J R, Scaife A A, Lu Y, Wu T, Gray L J and Schenzinger V 2019 Observed and simulated teleconnections between the stratospheric quasi-biennial oscillation and Northern Hemisphere winter atmospheric circulation *J. Geophys. Res.* **124** 1219–32
- Ayarzagüena B and Screen J A 2016 Future Arctic sea ice loss reduces severity of cold air outbreaks in midlatitudes *Geophys. Res. Lett.* **43** 2801–9
- Bailey H, Hubbard A, Klein E S, Mustonen K-R, Akers P D, Marttila H and Welker J M 2021 Arctic sea-ice loss fuels extreme European snowfall *Nat. Geosci.* **14** 283–8
- Baxter I *et al* 2019 How tropical Pacific surface cooling contributed to accelerated sea ice melt from 2007 to 2012 as ice is thinned by anthropogenic forcing *J. Clim.* **32** 8583–602
- Calvo N, Iza M, Hurwitz M M, Manzini E, Peña-Ortiz C, Butler A H, Cagnazzo C, Ineson S and Garfinkel C I 2017 Northern hemisphere stratospheric pathway of different El Niño flavors in stratosphere-resolving CMIP5 models *J. Clim.* **30** 4351–71
- Chen R, Dai G, Liu R and Wang L 2021 Seasonal influence of the atmosphere and ocean on the fall sea ice extent in the Barents-Kara Seas *J. Geophys. Res.* **126** e2021JD035144
- Chen W, Yang S and Huang R-H 2005 Relationship between stationary planetary wave activity and the East Asian winter monsoon *J. Geophys. Res.* **110** D14110
- Cohen J *et al* 2020 Divergent consensus on Arctic amplification influence on mid-latitude severe winter weather *Nat. Clim. Change* **10** 20–29
- Cohen J, Agel L, Barlow M, Garfinkel C I and White I 2021 White linking Arctic variability and change with extreme winter weather in the United States *Science* **373** 1116–21
- Collins T W, Wang W Q and Kumar A 2018 Simulations of Eurasian winter temperature trends in coupled and uncoupled CFSv2 *Adv. Atmos. Sci.* **35** 14–26
- Coumou D and Rahmstorf S 2012 A decade of weather extremes *Nat. Clim. Change* **2** 491–6
- Ding S, Wu B and Chen W 2021 Dominant characteristics of early autumn Arctic sea ice variability and its impact on winter Eurasian climate *J. Clim.* **34** 1825–46
- Docquier D and Koenigk T 2021 A review of interactions between ocean heat transport and Arctic sea ice *Environ. Res. Lett.* **16** 123002
- Domeisen D I V, Garfinkel C I and Butler A H 2019 The teleconnection of El Niño Southern oscillation to the stratosphere *Rev. Geophys.* **57** 5–47
- Dunstone N, Smith D, Scaife A, Hermanson L, Eade R, Robinson N, Andrews M and Knight J 2016 Skilful predictions of the winter North Atlantic oscillation one year ahead *Nat. Geosci.* **9** 809–14
- Elsbury D, Peings Y and Magnusdottir G 2021 CMIP6 models underestimate the Holton-Tan effect *Geophys. Res. Lett.* **48** e2021GL094083
- Free M and Seidel D J 2009 Observed El Niño-Southern oscillation temperature signal in the stratosphere *J. Geophys. Res.* **114** D23108
- Garfinkel C I, Hartmann D L and Sassi F 2010 Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices *J. Clim.* **23** 3282–99
- Gong D-Y, Wang S-W and Zhu J-H 2001 East Asian winter monsoon and Arctic oscillation *Geophys. Res. Lett.* **28** 2073–6
- Hardiman S C, Dunstone N J, Scaife A A, Smith D M, Knight J R, Davies P, Claus M and Greatbatch R J 2020 Predictability of European winter 2019/20: Indian Ocean dipole impacts on the NAO *Atmos. Sci. Lett.* **21** e1005
- Hirschi J and Sinha B 2007 Negative NAO and cold Eurasian winters: how exceptional was the winter of 1962/1963? *Weather* **62** 43–48

- Holton J R and Tan H-C 1980 The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 Mb *J. Atmos. Sci.* **37** 2200–8
- Hoshi K, Ukita J, Honda M, Iwamoto K, Nakamura T, Yamazaki K, Dethloff K, Jaiser R and Handorf D 2017 Poleward eddy heat flux anomalies associated with recent Arctic sea ice loss *Geophys. Res. Lett.* **44** 446–54
- Ineson S and Scaife A A 2009 The role of the stratosphere in the European climate response to El Nino *Nat. Geosci.* **2** 32–36
- Jaiser R, Dethloff K and Handorf D 2013 Stratospheric response to Arctic sea ice retreat and associated planetary wave propagation changes *Tellus A* **65** 19375
- Kamo K, Konoshima M and Yoshimoto A 2016 Statistical analysis of tree-forest damage by snow and wind: logistic regression model for tree damage and cox regression for tree survival *Formath* **15** 44–55
- Kim B-M, Son S-W, Min S-K, Jeong J-H, Kim S-J, Zhang X, Shim T and Yoon J-H 2014 Weakening of the stratospheric polar vortex by Arctic sea-ice loss *Nat. Commun.* **5** 4646
- Kobayashi S et al 2015 The JRA-55 reanalysis: general specifications and basic characteristics *J. Meteorol. Soc. Japan* **93** 5–48
- Kumar V, Yoden S and Hitchman M H 2022 QBO and ENSO effects on the mean meridional circulation, polar vortex, subtropical westerly jets, and wave patterns during boreal winter *J. Geophys. Res.* **127** e2022JD036691
- Li Y H, Xu H M and Liu D 2011 Features of the extremely severe drought in the east of Southwest China and anomalies of atmospheric circulation in summer 2006 *Acta Meteorol. Sin.* **25** 176–87
- Liu J P, Curry J A, Wang H J, Song M R and Horton R M 2012 Impact of declining Arctic sea ice on winter snowfall *Proc. Natl Acad. Sci. USA* **109** 4074–9
- Liu Y, Zhu Y, Wang H, Gao Y, Sun J, Wang T, Ma J, Yurova A and Li F 2019 Role of autumn Arctic sea ice in the subsequent summer precipitation variability over East Asia *Int. J. Climatol.* **40** 706–22
- Lu H, Hitchman M, Gray L, Anstey J and Osprey S 2020 On the role of Rossby wave breaking in the quasi-biennial modulation of the stratospheric polar vortex during boreal winter *Q. J. R. Meteorol. Soc.* **146** 1939–59
- Lu Q, Rao J, Shi C H, Guo D, Wang J, Liang Z Q and Wang T 2022 Observational subseasonal variability of the PM_{2.5} concentration in the Beijing-Tianjin-Hebei area during the January 2021 sudden stratospheric warming *Adv. Atmos. Sci.* **39** 1623–36
- Ma T, Chen W, Huangfu J, Song L and Cai Q 2021 The observed influence of the quasi-biennial oscillation in the lower equatorial stratosphere on the East Asian winter monsoon during early boreal winter *Int. J. Climatol.* **41** 1–16
- McCusker K E, Fyfe J C and Sigmond M 2016 Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss *Nat. Geosci.* **9** 838–42
- Meier W N, Peng G, Scott D J and Savoie M H 2014 Verification of a new NOAA/NSIDC passive microwave sea-ice concentration climate record *Polar Res.* **33** 21004
- Miao J P and Wang T 2020 Decadal variations of the East Asian winter monsoon in recent decades *Atmos. Sci. Lett.* **21** e960
- Mitchell D M, Gray L J and Charlton-Perez A J 2011 The structure and evolution of the stratospheric vortex in response to natural forcings *J. Geophys. Res.* **116** D15110
- Mori M, Watanabe M, Shiogama H, Inoue J and Kimoto M 2014 Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades *Nat. Geosci.* **7** 869–73
- Nakamura T, Yamazaki K, Iwamoto K, Honda M, Miyoshi Y, Ogawa Y, Tomikawa Y and Ukita J 2016 The stratospheric pathway for Arctic impacts on midlatitude climate *Geophys. Res. Lett.* **43** 3494–501
- Overland J E, Dethloff K, Francis J A, Hall R J, Hanna E, Kim S-J, Screen J A, Shepherd T G and Vihma T 2016 Nonlinear response of mid-latitude weather to the changing Arctic *Nat. Clim. Change* **6** 992–9
- Overland J, Francis J A, Hall R, Hanna E, Kim S-J and Vihma T 2015 The melting Arctic and midlatitude weather patterns: are they connected? *J. Clim.* **28** 7917–32
- Peings Y and Magnusdottir G 2014 Response of the wintertime Northern Hemisphere atmospheric circulation to current and projected Arctic sea ice decline: a numerical study with CAM5 *J. Clim.* **27** 244–64
- Perlwitz J, Hoerling M and Dole R 2015 Arctic tropospheric warming: causes and linkages to lower latitudes *J. Clim.* **28** 2154–67
- Rao J, Garfinkel C I and White I P 2020 Impact of the quasi-biennial oscillation on the northern winter stratospheric polar vortex in CMIP5/6 models *J. Clim.* **33** 4787–813
- Rao J, Garfinkel C I and White I P 2021 Development of the extratropical response to the stratospheric quasi-biennial oscillation *J. Clim.* **34** 7239–55
- Rao J and Ren R C 2016a A decomposition of ENSO's impacts on the northern winter stratosphere: competing effect of SST forcing in the tropical Indian Ocean *Clim. Dyn.* **46** 3689–707
- Rao J and Ren R C 2016b Asymmetry and nonlinearity of the influence of ENSO on the northern winter stratosphere: 1. Observations *J. Geophys. Res.* **121** 9000–16
- Rayner N A et al 2003 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century *J. Geophys. Res.* **108** 4407
- Ren R C, Rao J, Wu G X and Cai M 2017 Tracking the delayed response of the northern winter stratosphere to ENSO using multi reanalyses and model simulations *Clim. Dyn.* **48** 2859–79
- Ren R-C, Cai M, Xiang C Y and Wu G X 2012 Observational evidence of the delayed response of stratospheric polar vortex variability to ENSO SST anomalies *Clim. Dyn.* **38** 1345–58
- Richter J H, Anstey J A, Butchart N, Kawatani Y, Meehl G A, Osprey S and Simpson I R 2020 Progress in simulating the quasi-biennial oscillation in CMIP models *J. Geophys. Res.* **125** e2019JD032362
- Screen J A, Deser C, Simmonds I and Tomas R 2014 Atmospheric impacts of Arctic sea-ice loss, 1979–2009: separating forced change from atmospheric internal variability *Clim. Dyn.* **43** 333–44
- Semenov V A and Latif M 2015 Nonlinear winter atmospheric circulation response to Arctic sea ice concentration anomalies for different periods during 1966–2012 *Environ. Res. Lett.* **10** 054020
- Smith D M, Cusack S, Colman A W, Folland C K, Harris G R and Murphy J M 2007 Improved surface temperature prediction for the coming decade from a global climate model *Science* **317** 796–9
- Son S-W, Lim Y, Yoo C H, Hendon H H and Kim J 2017 Stratospheric control of the Madden-Julian oscillation *J. Clim.* **30** 1909–22
- Sun L T, Deser C and Tomas R A 2015 Mechanisms of stratospheric and tropospheric circulation response to projected Arctic sea ice loss *J. Clim.* **28** 7824–45
- Sun L, Perlwitz J and Hoerling M 2016 What caused the recent “warm Arctic, cold continents” trend pattern in winter temperatures? *Geophys. Res. Lett.* **43** 5345–52
- Sung M-K, Lim G-H and Kug J-S 2010 Phase asymmetric downstream development of the North Atlantic oscillation and its impact on the East Asian winter monsoon *J. Geophys. Res.* **115** D09105
- Tang Q H, Zhang X J, Yang X H and Francis J A 2013 Cold winter extremes in northern continents linked to Arctic sea ice loss *Environ. Res. Lett.* **8** 014036
- Thornton H, Brayshaw D, Hoskins B J and Scaife A A 2017 The relationship between wind power, electricity demand and winter weather patterns in Great Britain *Environ. Res. Lett.* **12** 064017
- Wang G Z, Wu L Y and Chen J B 2016 Intensity and economic loss assessment of the snow, low-temperature and frost disasters: a case study of Beijing City *Nat. Hazards* **84** 293–307

- Wang H J and He S P 2012 Weakening relationship between East Asian winter monsoon and ENSO after mid-1970s *Chin. Sci. Bull.* **57** 3535–40
- Warner J, Screen J A and Scaife A A 2019 Links between Arctic sea ice and the extratropical atmospheric circulation explained by internal variability and tropical forcing *Geophys. Res. Lett.* **47** e2019GL085679
- Wu B Y 2018 Progresses in the impact study of Arctic sea ice loss on wintertime weather and climate variability over East Asia and key academic disputes *Chin. J. Atmos. Sci.* **42** 786–805
- Wu B Y, Handorf D, Dethloff K, Rinke A and Hu A X 2013 Winter weather patterns over Northern Eurasia and Arctic sea ice loss *Mon. Weather Rev.* **141** 3786–800
- Wu B Y, Su J Z and D'Arrigo R 2015 Patterns of Asian winter climate variability and links to Arctic sea ice *J. Clim.* **28** 6841–58
- Wu B Y, Su J Z and Zhang R H 2011 Effects of autumn–winter Arctic sea ice on winter Siberian high *Chin. Sci. Bull.* **56** 3220–8
- Xie J B, Zhang M H and Liu H L 2019 Role of Arctic sea ice in the 2014–2015 Eurasian warm winter *Geophys. Res. Lett.* **46** 337–45
- Xu M, Tian W, Zhang J, Screen J A, Huang J, Qie K and Wang T 2021 Distinct tropospheric and stratospheric mechanisms linking historical Barents–Kara sea-ice loss and late winter Eurasian temperature variability *Geophys. Res. Lett.* **48** e2021GL095262
- Yamazaki K, Nakamura T, Ukita J and Hoshi K A 2020 Tropospheric pathway of the stratospheric quasi-biennial oscillation (QBO) impact on the boreal winter polar vortex *Atmos. Chem. Phys.* **20** 5111–27
- Yang H, Rao J and Chen H 2022 Possible lagged impact of the Arctic sea ice in Barents–Kara seas on June precipitation in Eastern China *Front. Earth Sci.* **10** 886192
- Zhang J K, Tian W S, Chipperfield M P, Xie F and Huang J L 2016 Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades *Nat. Clim. Change* **6** 1094–9
- Zhang J K, Xie F, Ma Z C, Zhang C Y, Xu M, Wang T and Zhang R H 2019 Seasonal evolution of the quasi-biennial oscillation impact on the Northern Hemisphere polar vortex in winter *J. Geophys. Res.* **124** 12568–86
- Zhang P F, Wu Y T, Simpson I R, Smith K L, Zhang X D, De B and Callaghan P 2018b A stratospheric pathway linking a colder Siberia to Barents–Kara Sea sea ice loss *Sci. Adv.* **4** eaat6025
- Zhang P F, Wu Y T and Smith K L 2018a Prolonged effect of the stratospheric pathway in linking Barents–Kara Sea sea ice variability to the midlatitude circulation in a simplified model *Clim. Dyn.* **50** 527–39
- Zhang R, Tian W and Wang T 2020 Role of the quasi-biennial oscillation in the downward extension of stratospheric northern annular mode anomalies *Clim. Dyn.* **55** 595–612
- Zheng F et al 2022 The 2020/21 extremely cold winter in China influenced by the synergistic effect of La Niña and warm Arctic *Adv. Atmos. Sci.* **39** 546–52
- Zhou X, Li J P, Xie F, Chen Q L, Ding R Q, Zhang W X and Li Y 2018 Does extreme El Niño have a different effect on the stratosphere in boreal winter than its moderate counterpart? *J. Geophys. Res.* **123** 3071–86