A link of China warming hiatus with the winter sea ice loss in Barents–Kara Seas

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Abstract
Since the late 1990s, the global warming has ground to a halt, which has sparked a rising interest among the climate scientists. The hiatus is not only observed in the globally averaged surface air temperature (SAT), but also in the China winter temperature trend, which turns from warming during 1979–1997 to cooling during 1998–2013. However, the reasons and the relevant mechanisms of the warming hiatus are far from being understood. Arctic sea ice (ASI), one of the tipping points of the Earth system change, has contributed to the dramatic climate change. It is found that the ASI over the Barents–Kara Seas in the warming hiatus period (1998–2013) has declined about three times faster than that in the previous continuing warming period (1979–1997). The observational analysis and the wave ray trajectories suggest that, for the hiatus period, the ASI over the Barents-Kara Seas explains 61.4% of the decreasing SAT trend and 14.4% of the interannual SAT variation in China. The possible dynamical process is as follows: the anomalous ASI loss associated with the significant warming in Barents-Kara Seas can excite a downstream teleconnection wave train pattern over the Eurasia continent. The significant easterly winds in the subpolar region slacken the polar-front jet, while the anomalous westerly winds over the Tibetan Plateau reinforce the East Asian subtropical jet. As a result, the concurrent out-of-phase variations in the intensity of the jets lead to the cold flow moving southward from the Arctic and converging in China. The northwest–southeast tilted dipole pattern of the height centers over Eurasia, accompanied with the weakened polar-front jet, usually favors the persistence of Ural blocking (UB). Furthermore, in the lower level, the anomalous high pressure belt over the northern Eurasian continent can help cold northeasterly winds blow from the Russian Far East to China and bring about the cold winters. Thus, the accelerated melting of ASI can exert a profound influence on China warming hiatus in recent two decades.

Keywords Arctic sea ice · China warming hiatus · Wave train pattern · Jets · Ural blocking

1 Introduction

Despite the accelerated greenhouse gas emissions due to the anthropogenic forcing, the average global temperature has slowed down its rising step since the end of the twentieth century, in sharp contrast to the continued warming over the whole twentieth century (Easterling and Wehner 2009; Foster and Rahmstorf 2011). The slowdown in the temperature trend during the recent two decades is known as the “warming hiatus” (Fyfe et al. 2013a), “pause” (Lewandowsky et al. 2016), or “global slowdown” (Guemas et al. 2013). Although this “stopped” phenomenon remains debated (Cowtan and Way 2014; Karl et al. 2015; Lewandowsky et al. 2015), it has attracted a lot of attentions of the climate scientists and the policymakers.

Various mechanisms have been proposed to explain the recent hiatus in the global warming, including the external
forcing and the internal climate variability. The reduced solar radiation in the diminishing phase of the sunspot numbers (Lean and Rind 2009; Fröhlich 2012), the volcanic eruptions in the late twentieth- and early twenty-first-century (Solomon et al. 2011; Fyfe et al. 2013a, b; Haywood et al. 2014; Santer et al. 2014), and the decreased stratospheric water vapor (Solomon et al. 2010) act as the potential external forcings to slack the pace of the surface warming. As the prominent internal variability of the coupled system, the varied distribution of heating within the ocean is the crucial factor of the global temperature variation. Recent studies reveal that the El Niño–Southern Oscillation (ENSO) (Meehl et al. 2011; Balmaseda et al. 2013; Ogata et al. 2013; Risbey et al. 2014), the Pacific Decadal Oscillation (PDO) or the Interdecadal Pacific Oscillation (IPO) (Meehl et al. 2011, 2013, 2014, 2016; Kosaka and Xie 2013; Trenberth et al. 2014; Dai et al. 2015; Steinman et al. 2015), and the distinct enhanced trade winds in the tropical Pacific (England et al. 2014; Watanabe et al. 2014) could have substantial contributions to the hiatus. Chen and Tung (2014) found that the anomalous salinity-induced heat sink can penetrate to the deeper layers in the Atlantic and the Southern oceans during the episode of hiatus. The role of the Atlantic warming may be more important than the Pacific cooling, and the latter may be considered as the response to the former (Jaccard 2012; Chen and Tung 2014; McGregor et al. 2014; Liu and Sui 2014). Li et al. (2013b) showed that the North Atlantic Oscillation (NAO) has a delayed effect on the Atlantic Multidecadal Oscillation (AMO) through the slow oceanic processes and can provide a good predictor for the Northern Hemisphere warming hiatus. Some literature also indicates that the Indian Ocean and the Antarctic bottom water favour this hiatus phenomenon (Meehl et al. 2013; Song et al. 2014).

Among all the forcings, Arctic impact is less documented. Arctic sea ice (ASI) is not only the imperative indicator of the global climate change but also has a dramatic influence on the Earth system (Lenton et al. 2008; Vihma 2014). Since the post-satellite era, the ASI cover has declined rapidly at an increasing rate (~10.1% per decade) in 1996–2007, almost five times as fast as that (~2.2% per decade) in 1979–1996 (Comiso et al. 2008, 2012; Bader et al. 2011). The summer sea ice reached its minimum record in 2005, 2007 and 2012 (Honda et al. 2009; Tang et al. 2013), and the winter ice extent has been considerably lower than the climatology since the early 2000s (Vihma 2014). Many observational and modeling studies suggested that the recent severe winters in the mid-latitudes are intimately related to the ASI variation and Arctic warming via the changes in storm tracks, NAO or Arctic Oscillation (AO) phase, the jet stream, and the propagation of planetary waves (Honda et al. 2009; Petoukhov and Semenov 2010; Wu et al. 2011, 2013; Liu et al. 2012b; Li and Wu 2012; Cohen et al. 2012, 2014; Tang et al. 2013; Mori et al. 2014). On the intraseasonal timescale, the Barents-Kara Seas warming associated with the sea ice loss plays an important role in the Eurasian cold winters, which is closely linked to the positive NAO phase and quasi-stationary Ural blocking (UB) events (Luo et al. 2016a, b, 2017a, b; Yao et al. 2017). These harsh winters induced by the diminished ASI can hamper the continued warming locally even globally. However, the quantification of the Arctic role in the cold continents has not yet demonstrated, especially when the ASI loss is faster than before in the global warming hiatus period. So, it is worthwhile to investigate the potential influence of the ASI interdecadal change and its quantitative contribution.

The temperature-rising hiatus not only takes place worldwide or in the certain ocean, but also occurs prominently over land, especially in mid-high latitudes of Northern Hemisphere (Huang et al. 2017). Previous studies indicated that the winter “warm Arctic–cold Eurasian” pattern has become remarkably since the late 1990s (Overland et al. 2011; Francis and Vavrus 2012; Kug et al. 2015; Luo et al. 2016a, b; Yao et al. 2017). As a part of the Eurasian continent, China has also experienced the warming hiatus, represented by the cooling trend of surface air temperature (SAT) during the 1998–2012 period (Li et al. 2010a, b, 2015a; Cao et al. 2013; Wang et al. 2014). The linkage between the ASI and the winter climate variability in China on the interannual timescale has been investigated by many researchers (Liu et al. 2007, 2012a; Zuo et al. 2016; Wang and Chen 2014). But the climate response to the interdecadal change of the ASI trend and the quantitative contribution of the ASI remain unclear. Since the late 1990s, the ASI has shrunk quickly, while the winter temperature in China has leveled off. So, can the sharp downtrend of ASI prompt China warming hiatus? What proportion can the ASI change account for China cooling trend? And how can the ASI anomalies influence China warming slowdown? These are three key questions we attempt to answer in this study.

This paper is organized as follows. Section 2 describes the data and the methodology used in this study. To figure out the relationship between the ASI and China winter SAT, we investigate their variations and the atmospheric circulation anomalies related to the ASI loss in different periods in Sect. 3. Section 4 discusses the possible physical mechanism by analyzing the anomalous propagation of the wave energy flux. The wave ray tracing method is also adopted to demonstrate the ASI remote forcing on the downstream circulation. The main conclusions and discussions are presented in Sect. 5.

### 2 Data and methods

The monthly temperature data based on the 160 gauges are obtained from China Meteorological Administration (CMA). The sea ice concentrations are provided by the China Meteorological Administration (CMA). The sea ice concentrations are provided by the
Met Office Hadley Centre with a resolution of 1.0° × 1.0°. The monthly mean atmospheric circulations and 2-m temperature (T2m) utilize the monthly ERA-Interim data on a 2.0° × 2.0° grid. The daily 500-hPa geopotential height data are also taken from the ERA-Interim data on a 1.0° × 1.0° grid. Since the sea ice data are reliable during the post-satellite era and the warming pause occurred during 1998–2013, the period from 1979 to 2013 is analyzed here. In this study, the whole period is divided into two epochs: the warming epoch (1979–1997) and the hiatus epoch (1998–2013). The winter refers December, January and February (DJF). Since the El Niño–Southern Oscillation (ENSO) is the strongest natural interannual climate signal and has a widespread effect on the global climate change (Ding and Li 2011; Ding et al. 2017), we linearly removed the ENSO impact by detrending the winter Nino-3.4 index. Previous studies also indicated that the North Atlantic is an important source for the Eurasian climate change (Sato et al. 2014; Simmonds and Govekar 2014; Kug et al. 2015; Luo et al. 2016a). Based on the sea surface temperature (SST) anomaly regressed to the ASI index (ASI) in different periods (Figures omitted), we defined the tripole SST index in North Atlantic as the difference between the averaged SST in the positive regression box (20°–35°N, 15°–30°W) and the sum of averaged SST in two negative boxes (50°–70°N, 20°–65°W; 35°–50°N, 40°–80°W). In Sects. 3 and 4, to check how much the circulation pattern related to the ASI is sensitive to the upstream signals, we calculated the partial regression of the circulation pattern to the ASI after linearly removing the tripole SST index. The definition of ASII is demonstrated in Sect. 3.

The simple linear regression method is used to identify the trends of ASI and China SAT during different periods, which are represented by the regression coefficients or slopes. To further assess the trends, the Mann–Kendall (MK) non-parametric trend test is also adopted to evaluate the monotonic upward or the downward tendency of these variables (Mann 1945; Kendall 1975). To derive the leading mode of China SAT, the Empirical Orthogonal Function (EOF) analysis is employed for different periods. The EOF analysis is based on a covariance matrix.

The significance of correlation or regression between two autocorrelated time series is tested by using the effective degree of freedom (N_{edof}), which is given by the theoretical approximation (Zwiers and Storch 1995; Bretherton et al. 1999): 

\[ N_{edof} \approx \frac{N(1-R_1 R_2)}{1+R_1 R_2}, \]

where \( N_{edof} \) is effective sample size and \( N \) is the original sample size. Note that \( N_{edof} \) should be less than or equal to \( N - 2 \). \( R_1 \) and \( R_2 \) are the lag-1 autocorrelation coefficients of the two time series.

To identify the UB events, we used the one-dimensional blocking index of Tibaldi and Molteni (1990), as used by Gong and Luo (2017). The index is defined in terms of the 500-hPa geopotential height (Z) gradients to the north (GHGN) and south (GHGS):

\[
\text{GHGS} = \frac{Z(\phi_0) - Z(\phi_s)}{\phi_0 - \phi_s}
\]

(1)

\[
\text{GHGN} = \frac{Z(\phi_N) - Z(\phi_0)}{\phi_N - \phi_0}
\]

(2)

where \( \phi_N = 80^\circ N + \Delta, \phi_0 = 60^\circ N + \Delta, \text{and } \phi_s = 40^\circ N + \Delta \). Here, \( \Delta = -5^\circ, 0^\circ, \text{or } 5^\circ \) is used. A given longitude is said to be blocked at a given time if the following criteria is satisfied, that is GHGS > 0 and GHGN < −10 gpm (°lat −1). And a blocking event is occurred if the blocked conditions can persist for at least three consecutive days. The persisting days are defined as the blocking duration or the blocking days. The domain covers the region from 40° to 80°E because of the UB events centered at 60°E (Diao et al. 2006; Yao et al. 2017). The sum of the blocking days of each blocking event over the UB domain in winter is calculated as the UB frequency.

In addition, we also calculated the strength and vertical shear (VS) of the mean westerly wind (MWW) over the Ural Mountains, and the subtropical MWW over the Tibetan Plateau. In the subpolar region, the key area is over 50°–70°N, 30°–90°E (UB region hereafter), where the variations of westerly winds and the UB events are significant. In the subtropics, the jet over the Tibetan Plateau (TP) is an important part of the East Asian subtropical jets. Thus, the TP region (25°–35°N, 70°–110°E) is another study area. The vertically averaged MWW between 200 and 400 hPa (600 and 850 hPa) is defined as the upper (lower) tropospheric zonal winds U_U (U_L). The winter VS index (VSI) indicates the difference of U_U and U_L in the UB region. The subpolar MWW index (MWWPI) and the subtropical MWW index (MWWTI) are designated as the U_U in the UB region and the TP region, respectively.

To make the physical mechanism more robust, the methods of measuring the wave energy propagation are used. Following Takaya and Nakamura (2001), the propagation of wave activity flux (WAF) associated with the anomalous ASI is depicted to describe the ASI remote forcing.

Rossby wave ray tracing theory is also employed to analyze the possible wave paths associated with the heating perturbation. Based on the linearized barotropic non-divergent vorticity equation, the Wentzel–Kramers–Brillouin (WKB) approximation is used (e.g. Karoly 1983; Li and Nathan 1997; Li and Li 2012; Li et al. 2013a, 2015b; Zhao et al. 2015), which requires a time-mean slowly varying basic state. The dispersion relation describing the propagation features of perturbations is as follows:
The relationship between the ASI and China SAT in winter

3.1 Trends of China SAT and ASI

Figure 1 shows China SAT linear trends in winter for 1979–1997 and 1998–2013 periods, respectively. In Fig. 1a, there are significant increasing trends of SAT across the whole country except a few scattered gauges during 1979–1997. The high values mainly lie in the northeast of China with the maximum exceeding 2 °C per decade. While in 1998–2013, the warming trend has ground to a halt (Fig. 1b). The cooling trend controls China except the Tibetan plateau and adjacent areas. The minimum of the decreasing drift, below −2 °C per decade, is still situated in Northeast China. Due to the consistent

\[ \sigma = \bar{u}_M k + \bar{v}_M l + \frac{\bar{q}_l - \bar{q}_k}{k^2 + l^2} \quad (3) \]

where \((\bar{u}_M, \bar{v}_M) = (\bar{u}, \bar{v})/\cos \varphi\) are the zonal and meridional component of the basic flow on a Mercator projection, \(\bar{q}_l, \bar{q}_k\) are the zonal and meridional gradients of the basic state absolute vorticity, \(k, l, \sigma\) are the zonal wavenumber, meridional wavenumber, and the angular frequency, respectively. For stationary waves, the total wavenumber is defined as:

\[ K^2 = \frac{\bar{q}_k l - \bar{q}_l k}{\bar{u}_M k + \bar{v}_M l} \quad (4) \]

Following Lighthill (1978), the ray path is a trajectory locally tangent to the group velocity vector. Thus, the ray trajectories can reflect the energy propagation. The longitudinal and latitudinal variation of the basic state indicates that both \(l\) and \(k\) change along the ray paths. Derived from the kinematic wave theory (Whitham 1960), the evolution of the wavenumbers takes the form:

\[ u_g = \frac{\partial \sigma}{\partial k} = \bar{u}_M + \frac{(k^2 - l^2) \bar{q}_l - 2lk \bar{q}_k}{K^4} \quad (5) \]

\[ v_g = \frac{\partial \sigma}{\partial l} = \bar{v}_M + \frac{2lk \bar{q}_l + (k^2 - l^2) \bar{q}_k}{K^4} \quad (6) \]

The zonal and meridional components of group velocity have the form:

\[ \frac{d\bar{u}_M}{dT} = -k \frac{\partial \bar{v}_M}{\partial X} = -k \frac{\partial \bar{v}_M}{\partial X} \quad (7) \]

\[ \frac{d\bar{v}_M}{dT} = -k \frac{\partial \bar{u}_M}{\partial Y} = -k \frac{\partial \bar{u}_M}{\partial Y} \quad (8) \]

where \(\frac{d}{dt} = \frac{d}{dt} + u \frac{d}{dx} + v \frac{d}{dy}\) represents the Lagrangian variation moving at the group velocity. Given the initial latitude and longitude, the initial zonal wave number, the ray trajectory can be integrated through Eqs. (5)–(8). The initial meridional wave number is obtained through Eq. (3) or (4).

The ray trajectories are widely used to clarify the atmospheric teleconnection mechanism (e.g., Sun et al. 2015; Wu et al. 2016; Zhou et al. 2017). The trajectory of the wave ray intimately depends on the basic state. In this study, the climatological mean states in winter for the 1979–2013 and 1998–2013 periods are fixed as basic states respectively.

Fig. 1 The spatial pattern of China SAT linear trend (°C/decade) in a 1979/1980–1997/1998 and b 1998/1999–2013/2014 winters based on the 160-station data. The trends are represented by the dots with different sizes and colors. The cold (warm) color indicates the negative (positive) trend. The Tibetan Plateau is displayed with the green curve. The cross symbol in b indicates the station is located at the altitude higher than 2500 meters
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warming trends in a few stations over the Tibetan Plateau, the hiatus may not occur in this area. Thus, we exclude the twelve stations marked by the cross symbol in the following calculation (Fig. 1b). As shown in Fig. 1, the level-off China SAT since the late 1990s is a large transformation from the positive trend pattern into a dominant negative trend pattern. We also examined the trends of the annual mean SAT and the seasonal mean SAT in spring, summer and autumn (Figures omitted). It can be found that China has experienced the warming stage throughout the year over 1979–1997, with the most striking warming trend in winter. For the period 1998–2013, the warming pause is not consistent in different seasons. The cooling tendency is most significant in winter, while the Yangtze river basin is still dominated by the continuously increasing SAT in summer. Thus, the regional warming hiatus is a key feature in the cold season. Winter is chosen as the target season in this study.

To identify the sea ice change in winter, the trends and the standard deviations (STD) of ASI are depicted for two stages. In the 1979–1997 period, the sea ice experienced the growing trend in the Arctic region except the eastern Barents Sea, the Gulf of Bothnia and the Davis Strait (Fig. 2a). The Barents Sea has the maximum declining rate of ice below 20% per decade. Since 1998, the melting tendency is dominant in the most regions of the Arctic, especially in the Barents-Kara Seas (Fig. 2b). Differing from the substantial change of the ASI trend in recent two decades, the predominant year-to-year variability of sea ice prevails in the Bering Sea, the Barents Sea, the Greenland Sea, and the Davis Strait throughout the whole period (Fig. 2c, d). Note that the sea-ice interannual variability over the former two

Fig. 2  The trends (%/decade) and standard deviations (%) of the winter ASI concentration for the periods (a), (c) 1979/1980–1997/1998 and (b, d) 1998/1999–2013/2014. Black box (70°–77°N, 35°–70°E) denotes the ASI key region
seas becomes stronger, while that over the latter two seas turns weaker. Figure 2 indicates that the sea ice over the Barents-Kara Seas manifests the consistent decreasing trends for these two periods, but the reduced rate of the sea ice has been accelerated significantly along with the strengthened year-to-year variability during 1998–2013. Therefore, the key region of ASI is chosen within the 70°–77°N, 35°–70°E in this study (as shown by the boxes in Fig. 2), generally in agreement with the work conducted by Kug et al. (2015).

3.2 Dominant modes of China SAT and the associated ASI variability

To further examine the relationship between China SAT and the ASI variability, we calculate the EOFs of China SAT for three periods and regress the ASI to the corresponding PCs. For the period 1979–2013 (Fig. 3a–c), the EOF1 of China SAT (49.7%) exhibits the overall growing temperature with the stronger warming in northern China. PC1 shows the considerable interdecadal variation around 1998, from the rising trend to the declining trend. The abnormal ASI associated with this SAT pattern primarily lies in the Seas near the Eurasia coast, with the maximum located in the Barents-Kara Seas. It suggests that the sea ice over the Barents-Kara Seas may be closely related to the China SAT variability. These characteristics are also evident in the separate periods. The first EOFs of China winter SAT during two epochs (1979–1997 and 1998–2013) all resemble that over 1979–2013. But the EOF1 in the latter period explains more variance (58.2%) and the amplified warming conspicuously occurs in Northeast China (Fig. 3g–i). Correspondingly, the PC1 presents the increasing tendency during 1979–1997

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Fig. 3  a Spatial pattern (EOF1, color shadings) and c the standard time series (PC1, color bars) of the first EOF mode of China winter SAT (°C) as well as b the ASI anomaly regressed to the PC1 during 1979–2013. d, e, f As a, b, c, but for the 1979–1997 period. g, h, i As a, b, c, but for the 1998–2013 period. Considering the effective freedom degree, the black (purple) dotted areas indicate the regressed anomalies beyond the 90% (85%) confidence level. The Black box denotes the ASI key region. The green dashed lines in e, f, i represent the linear trends of PC1s.
and turns to the decreasing tendency during 1998–2013. It implies that the China winter temperature has undergone the interdecadal change from the rapid warming to the moderate cooling, with the trend exceeding 99% and 80% confidence level based on the MK test respectively. Compared to the warming epoch, a large area of significant ASI anomalies is discerned over the Barents-Kara Seas in the cooling epoch, which indicates that the ASI loss may play a critical role in the China hiatus phenomenon. Stated thus, the EOF analysis further denotes the potential connection between the ASI over the Barents-Kara Seas and China SAT in winter. We also investigate the EOF2s of China winter SAT. For the period 1979–2013, EOF2 shows the dipole temperature pattern with the cooling center in northeastern China and the warming anomaly in most parts of China. The corresponding PC2 has an increasing trend. The substantially correlated ASI anomalies are situated in the Greenland Sea (positive), the northern Barents-Kara Seas (negative) and the southern Barents Sea (positive) (Figure omitted). The statistical relationship between the ASI and China SAT EOF2 is different from that with EOF1 during 1979–2013. We only focus on China SAT EOF1 in this study.

3.3 Definition of ASII and China SAT index (CTI)

Although the trend changes of ASI and China SAT in winter have been demonstrated by the above observational analysis, the relationship between them needs to be further investigated. Given the spatial pattern of ASI in Figs. 2 and 3, we defined the ASII by averaging the winter sea ice concentration in the Barents-Kara Seas (70°–77°N, 35°–70°E). CTI is calculated based on the winter mean SAT of 148 gauges in China. Owing to the inconsistent trends during two periods, 12 out of 160 stations over the Tibetan Plateau are removed. As shown in Fig. 4a, the ASII has rapidly declined over the hiatus period. The decreasing trend is −13.2% per decade, significant at the 95% confidence level based on the MK test. In contrast to the warming period, the ASII has stayed low since 2004. Correspondingly, the CTI converts from the warming tendency in 1979–1997 (0.81 °C per decade) to the cooling tendency in 1998–2013 (−0.83 °C per decade). The former trend exceeds the 99% confidence level based on the MK test, while the latter one fails the 85% significance test. It shows that China winter temperature has halted since 1998.

The correlation analysis is conducted to examine the potential connection between the ASI and China SAT in winter. During the whole period from 1979 to 2013, the correlation between ASII and CTI is 0.21 ($N_{edof} = 27$) and rises to 0.46 ($N_{edof} = 31$) after detrending these two indices. The latter is significant at the 99% confidence level based on the Student’s $t$ test. For the periods 1979–1997 and 1998–2013, the correlation coefficients are 0.13 ($N_{edof} = 14$) and 0.52 ($N_{edof} = 14$, beyond the 95% confidence level). When the indices eliminate their trends, the coefficients turn into 0.41 ($N_{edof} = 17$) and 0.38 ($N_{edof} = 14$), exceeding the 90% and 85% confidence level respectively. The intimate relationship between the ASI and China SAT at the interannual scale suggests that the ASI loss may lead to the decreased temperature in China. The ASI change can explain 21.2%, 16.8% and 14.4% of the interannual variations of the China SAT in the 1979–2013, 1979–1997 and 1998–2013 periods respectively. Thus, along with the abrupt melting ASI, China has experienced the cooling trend in the hiatus period. The strengthened ties can be implied by the increased coefficient (0.52).

3.4 Potential influence of ASI on China warming hiatus

Figure 5 shows the residual linear trend of China winter SAT after linearly removing the ASII during the hiatus period. Compared with Fig. 1b, the overall cooling trend in China becomes weakened obviously with many regions slightly warming up (Fig. 5a). The minimum centered near Northeast China in Fig. 1b disappears and shifts to Southeast China in Fig. 5a. It indicates that the winter temperature change in Northeast China is most sensitive to the ASI variability. The mild cooling and warming trends after eliminating the ASI impact illustrate that the faster ASI loss over the Barents-Kara Seas may hinder the continuous warming in China during 1998–2013. From the time series of CTI, the
black straight line denotes its linear variation with time, with the slope of −0.86 unit/decade. After the removal of the ASI impact, the residual CTI has a moderate trend that reduced to −0.22 unit/decade (Fig. 5b).

Table 1 Quantitative contribution of the declining winter ASI to the CTI trend for the periods 1979–1997 and 1998–2013

<table>
<thead>
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<tbody>
<tr>
<td>CTI trend (°C decade⁻¹)</td>
<td>0.81***</td>
<td>−0.83</td>
</tr>
<tr>
<td>Correlation (year-to-year differenced data)</td>
<td>0.41** (Nedof = 17)</td>
<td>0.38 * (Nedof = 14)</td>
</tr>
<tr>
<td>Sensitivity (°C unit⁻¹)</td>
<td>3.087** (Nedof = 17)</td>
<td>3.831* (Nedof = 14)</td>
</tr>
<tr>
<td>ASII Trend (unit decade⁻¹)</td>
<td>−0.041</td>
<td>−0.132***</td>
</tr>
<tr>
<td>Induced CTI trend (°C decade⁻¹)</td>
<td>−0.13</td>
<td>−0.51</td>
</tr>
<tr>
<td>Contribution (%) to the CTI trend</td>
<td>−16.0</td>
<td>61.4</td>
</tr>
</tbody>
</table>

The correlation between the year-to-year difference of CTI and ASII is calculated. The sensitivity is defined as the regression between the CTI and ASII after removing their linear trends. The CTI trend induced by the decreasing ASII is represented by the product of the sensitivity and the ASII trend in each period. Therefore, the contribution of ASII to the CTI trend is estimated by the ratio of the ASII-induced CTI trend to the observed CTI trend. The asterisks “*,” “**” and “***” represent the correlations (regressions, or trends) significant at the 85%, 90% and 95% confidence level, respectively.
with the detrended ASIs in two separate periods (Figure omitted). To compare the influence of the ASI trend, the anomalous responses to the original ASIs for the 1979–1997 and 1998–2013 periods are also examined. In the following analysis, the ASIs are reversed to represent the reduced ASI condition. And the ENSO and North Atlantic signal are linearly removed.

As shown in Fig. 6a, the year-to-year ASI loss is closely related to the strong warming over the Barents-Kara Seas and coldness in the midlatitudes. The cold anomalies are also evident in China, especially in northeastern China. Considering the ASI trend, the cold China associated with the slower sea–ice reduction is not significant during the warming period (Fig. 6b). When the sea ice decreases faster than before in the hiatus period, the amplitude of “warm Arctic–cold Eurasian” pattern becomes much larger (Fig. 6c), which is consistent with the previous findings (e.g., Overland et al. 2011; Francis and Vavrus 2012; Barnes 2013; Kug et al. 2015; Luo et al. 2016a). An intensified warming center is in the Barents-Kara Seas, and the most regions of China characterize the consistent stronger cooling variations (similar to Fig. 1). As indicated by previous studies (Honda et al. 2009; Petoukhov and Semenov 2010; Overland et al. 2011; Cohen et al. 2014), the sea–ice loss heats and moistens the local boundary layer, which can warm the atmospheric column as the heat source and be propitious to raise mid-tropospheric heights in the Barents-Kara Seas with a downstream trough over Eurasia.

Figure 7 presents the regression of winter sea level pressure (SLP) and 1000-hPa wind (UV1000) anomalies to the detrended ASII over 1979–2013 and the normalized ASIs over separate periods. As shown in Fig. 7a, on the interannual timescale, the Arctic region is dominated by the low pressure with cyclonic winds in the case of the diminished sea ice. Significant anticyclonic winds control the Eurasian continent, associated with the large-scale positive SLP belt in the mid latitudes. There are substantial northerly winds blowing from the Russian Far East to China. The anomalous northeasterly winds in eastern China can bring more cold air from the high latitudes and further lead to the decreased temperature in most regions of China. Besides, the high-pressure center seated near the Ural Mountains causes the cold northerly extending from Siberia, across the western Mongolian Plateau, to northwestern China, which favors the cold winters in northwestern China. In the previous continuing warming period, when the trend of sea–ice loss is relatively slower, the associated circulation anomaly is weaker in mid latitudes (Fig. 7b). Given the faster decreasing trend of ASI during 1998–2013, the circulation responses to the ASI change in Fig. 7c are similar to that in Fig. 7a but with more intensified anomalies, especially over the Eurasian continent. The heightened SLP and wind anomalies may lead to the amplified cooling state in China.

A distinct feature in Fig. 8a is that a prominent wave train pattern extends southeastward from the Barents-Kara Seas to China. Significant positive 500-hPa geopotential height (Z500) anomalies along with the anticyclonic winds stretch across Northern Eurasia. The substantial positive Z500 is centered near the Ural Mountains, where the UB events occur frequently. Different from the high-pressure anomalies at the lower level, marked negative Z500 anomaly with cyclonic winds prevails in China and the adjacent areas, which denotes the baroclinic structure at the lower and middle levels of the troposphere. The anticyclonic anomaly with the cyclone to its southeast is favorable for the long-lived northwest–southeast (NW–SE) oriented UB patterns, which can cause the intense, widespread and persistent Eurasian cooling (Luo et al. 2017b). Compared to Fig. 8a, the

![Figure 6](image_url)
teleconnection pattern responding to the slower ASI decline is weaker in Fig. 8b, especially the downstream center. Associated with much faster ASI reduction during 1998–2013, Fig. 8c represents more enlarged wave amplitude. The intensity of two pressure centers increases or decreases by more than 6 gpm. The enhanced response also reflects that the climate change in mid latitudes is more closely tied to the ASI change since 1998.

Figure 9 shows the winter 200-hPa geopotential height (Z200) and wind (UV200) anomalies regressed to the ASIIs. The anomalous circulation fields resemble those in Fig. 8.

Considering the interannual variability of ASI (Fig. 9a), there is a prominent wave train pattern propagating from the Arctic region to China, with the centers over the Barents-Kara Seas, the regions to the north and southwest of China. The positive Z200 anomaly over low latitudes is relatively indistinctive. Significant easterly winds lie around 50°–70°N, across the climatological polar-front jet region (not shown), which tends to slacken the zonal westerly winds. The zonal wind change is consistent with the results given by Gong and Luo (2017), Yao et al. (2017) and Luo et al. (2017c). The decelerated polar-front jet with larger meanders is propitious to the cold air flowing from Arctic to mid latitudes. In addition, a weaker and more meandering flow may induce the
slower movement of weather systems and further yield more persistent weather patterns (Barriopedro and García-Herrera 2006; Francis and Vavrus 2012). In the subtropics, abnormal westerly winds prevail over the Tibetan Plateau, which can help to reinforce the subtropical jet. This strengthened jet with a weaker meridional wind component may contribute to the cold flows converging in China and further lead to the cold situation. Thus, the concurrent out-of-phase variations of the polar-front jet and the subtropical jet jointly exert a profound influence on the cooling trend in China. In view of two separate periods, the change of jets related to the slower ASI melt is not significant for the previous period (Fig. 9b). Compared to Fig. 9a–b, accompanied with the amplified ASI thawing, the jet response turns out to be more remarkable for the latter period (Fig. 9c). The relationship between the out-of-phase variability of the upper level jets and China SAT was also referred by Xiao et al. (2016) and Zhang and Chen (2017). They also found that the dominant pattern of the weakened polar-front jet and the intensified subtropical jet experiences an interdecadal change and becomes more common around the early 2000s. This work further implies the crucial role of jets in China warming hiatus.

Since the UB frequency and the strength and vertical shear of upper-level westerly winds are intimately related to the widespread Eurasian cold events (Yao et al. 2017), we further investigate their relationships from the perspective of the indices (Fig. 10). We found that the ASII is well correlated with the UBI, VSI and MWWPI on the interannual timescale for the period 1979–2013. Their coefficients are $-0.51$ ($N_{\text{edof}} = 31$), $0.55$ ($N_{\text{edof}} = 33$) and $0.46$ ($N_{\text{edof}} = 33$) respectively, significant at 99% confidence level. In separated epochs, the correlations are still substantial. It suggests that the ASI loss can be closely related to the increased UB frequency, the weakened westerly winds and the diminished vertical shear in the UB region. These results are in agreement with the findings of Luo et al. (2016a) and Yao et al. (2017). In the previous continuing warming period, the trends of these four indices are not significant. During the hiatus period, with the faster ASI reduction, the UBI exhibits a significant increasing trend (6.14 day/decade), while the VSI and MWWPI represent the evident decreasing trends.
relationship is weak during 1979–1997 (−0.11, \(N_{\text{edof}} = 30\)) during 1979–2013. In different periods, their relationship is weak during 1979–1997 (−0.11, \(N_{\text{edof}} = 17\)) and becomes much stronger during 1998–2013 (−0.50, \(N_{\text{edof}} = 14\), exceeding 95% confidence level). The strengthened bond implies that ASI can exert a profound influence on the East Asian subtropical westerly jet and further modulate the local circulation in China during the hiatus stage. The significant interdecadal change may be closely related to the reduced polarward temperature gradient. The Arctic warming can induce a weaker zonal jet with larger meanders in the subpolar region and favors the energy dispersion between high latitudes and the mid-low latitudes. As such, the subtropical westerly jet may be more sensitive to the ASI variability under the background of Arctic amplification. The finding needs further investigation. Except for the more intimate interannual relationship with ASI, MWWTI also shows a remarkable growing trend (3.36 m s\(^{-1}\)/decade), corresponding to the rapidly shrinking ASI. The ASI can contribute 45.2% to the MWWTI trend.

From the above analysis, the anomalous T2m anomalies and circulation structure allow us to speculate the possible impact of the ASI change on China warming hiatus. On the interannual timescale, the reduction of ASI is generally followed by the warming condition over Barents-Kara Seas, which further modulates the local atmospheric circulation anomalies. In the upper level, a downstream Rossby wave train pattern is excited from the Arctic region, with the high pressure over the northern Eurasia and Barents-Kara Seas, and the low pressure over northern China and the Mongolian Plateau. The significant easterly winds in the subpolar region slacken the polar-front jet, while the anomalous westerly winds over the Tibetan Plateau reinforce the East Asian subtropical jet. As a result, the concurrent out-of-phase variations in the intensity of jets lead to the cold air moving southward from the Arctic and converging in China. Furthermore, the dipole pattern of the anticyclone in Northern Eurasia and the cyclone in China and the adjacent areas, along with the weakened polar-front jet, favor the maintenance of the NE–SW tilted UB and more frequent cold air outbreaks. At the lower level, the widespread positive SLP belt controls the northern Eurasian continent, which facilitates the cold northeasterly winds blowing from the Russian Far East to China. Thus, the decreased ASI may induce the cooling situation in China by modulating the downstream circulation fields. Considering the trend of ASI loss, the atmospheric responses to the faster sea–ice reduction during 1998–2013 are similar with more enhanced amplitude. The above dynamical process can also operate on the interdecadal timescale. So, the positive atmospheric feedback related to the ASI trend may facilitate the widespread intrusion of cold air and strongly hinder the continuous China warming. Different from the latter period, the coldness in China and the above circulation anomalies related to ASI change are inconspicuous during 1979–1997. It implies that, under the global warming background, the slower sea ice loss can only offset the China warming trend to a small extent. The ASI variability is not a primary factor for China SAT change in the warming period. Note that such speculation just relies on the statistical analysis and needs further verification.

4 Physical mechanism

To elucidate the above-mentioned mechanism that the accelerated melting ASI impacts on China cooling trend, we investigate the WAF propagation associated with the ASI change. Figure 11 presents the regressed WAF and stream function (SF) anomalies at 250 hPa associated with the detrended ASII in 1979–2013, the normalized ASII in 1979–1997 and 1998–2013. The WAF responses to the interannual variability of ASI are shown in Fig. 11a. In consideration of the rapid ASI decreasing trend (Fig. 11c), there is more significant WAF propagating southeastward from the Arctic region to China compared with Fig. 11a. During the hiatus period, the flux from the Barents-Kara Seas spreads downstream over the Eurasian continent. It intensifies over the Mongolian Plateau and to its west and is stimulated again in China. The obvious WAF prevails over East Asia, which indicates the ASI remote influence on modulating the local circulation systems in China. Correspondingly, the SF anomalies display a tripole wave train pattern along the direction of the northwest-southeast. Given the amplified impact of the ASI decreasing trend, the SF amplitude is also enlarged in comparison with that connected to the year-to-year variability of ASI. The above analysis manifests that the ASI anomaly plays a substantial role in China SAT change by exciting the downstream propagation of Rossby waves. Therefore, with the accelerated decrease of ASI, the continuous warming in China is hampered for the 1998–2013 period. Note that there is still WAF from the North Atlantic Ocean after linearly eliminating the North Atlantic signal. It is because that the involved nonlinear process of WAF anomaly can’t be completely removed by the linear regression. It also implies that North Atlantic is a source for the downstream climate change (e.g., Luo et al. 2015, 2016a, b). But considering the faster ASI reduction, the wave energy

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propagation from the Arctic is more significant during 1998–2013 (Fig. 11c). Different from the hiatus period, the wave energy from the high latitudes is not remarkable in the warming period, which indicates a small effect of the slower ASI loss on China SAT change under the background of global warming (Fig. 11b).

To further verify the possible mechanism referred above, the wave energy dispersion tied to the anomalous ASI is examined by the wave ray tracing method. Figure 12 displays the regressed Z200 to the low sea ice state (as in Fig. 10) and the wave ray trajectories for the 1979–2013 and 1998–2013 periods. The winter climatological flow in different periods is given as the background after a two-dimensional smooth truncated at zonal and meridional wavenumber 5. Wave rays are set to start from the area 60°–80°N, 45°–100°E at an interval of 2 grids, in order to check the possible propagation paths of local perturbations linked to the ASI anomalies. For the calculation of the wave ray trajectories, the initial zonal wavenumber is set 4, and then the meridional wavenumber can be derived by solving the dispersion relationship. Rays are terminated when the total wavenumber becomes larger than 40. By comparison between the ray results in the two epochs, it can be found in Fig. 12 that more starting points in the latter epoch have the second wave propagation trajectories, which indicates that the background state in 1998–2013 is more favorable for the wave propagation. The result shows that more wave energy associated with the rapidly declined sea ice can propagate from the Arctic region toward mid-latitudes in the hiatus epoch.

Generally, wave energy excited in this area disperses southeastward along two paths in both periods. One is directly from the Barents–Kara Seas toward the North Siberia. The other starts from Siberia, in the southeast of the positive Z200 anomaly. The former enhances the
atmospheric circulation responses in high latitudes, which favors more perturbations in Siberia. The latter is intimately related to the center downstream and further impacts the climate anomaly in China. This second path is consistent with the WAF anomaly that is strengthened over the Siberian region and propagates southeastward to China (Fig. 11).

Inferred from the wave propagation behaviors, the downstream atmospheric circulation is modulated, including the high center over the Barents-Kara Seas and the low center to the north of China. Thus, the polar-front jet associated with the anticyclonic winds weakens, while the East Asian subtropical jet associated with the cyclonic winds enhances. The increased probability for wave propagation in the hiatus period further confirms that the Barents-Kara Seas are crucial for the recent warming hiatus in China.

5 Conclusion and discussion

In this study, we devote to identifying the relationship between the winter ASI and China warming hiatus since the late 1990s. It is found that the winter SAT tendency in China turns from the warming (0.81 °C per decade) to the cooling condition (− 0.83 °C per decade) around 1998. Also, the winter sea ice over the Barents-Kara Seas reduced at the rate of − 13.2% per decade in 1998–2013, about three times faster than that in 1979–1997 (− 4.1% per decade). Hence, both the winter sea ice over the Barents-Kara Seas and China SAT experience the trend variation around 1998. The observational analysis shows that the accelerated ASI decline may be closely connected with China warming hiatus. At the interannual timescale, the year-to-year correlations between the ASI and China SAT
are $0.46 (N_{edof} = 31), 0.41 (N_{edof} = 17)$ and $0.38 (N_{edof} = 14)$ for the 1979–2013, 1979–1997 and 1998–2013 periods respectively. The ASI change can account for 21.2%, 16.8% and 14.4% of the interannual variations of the China SAT in the corresponding epochs. This interannual relationship is relatively robust. Considering the pronounced downward trend of ASI, the correlation coefficient is up to 0.52 ($N_{edof} = 14$) for the latter period, which suggests the stronger bonds between the ASI and China SAT. Through the quantitative measurement method, we found that the accelerated decline of ASI can explain 61.4% of the observed China cooling trend during 1998–2013.

To clarify the possible dynamical process, the linkage between the anomalous ASI and large-scale atmospheric modes was investigated. It is demonstrated that, in the hiatus period, the faster decreasing ASI can cause the evident warming in the Barents-Kara Seas and further excite a Rossby wave train pattern propagating from the Arctic region to China. The high pressure prevails from the coastal regions of the Barents-Kara Seas to the northern Eurasia, and the low pressure in northern China and the Mongolian Plateau. Correspondingly, the significant easterly winds in the subpolar region can weaken the polar-front jet, while the anomalous westerly winds over the Tibetan Plateau intensify the East Asian subtropical jet. Due to the concurrent out-of-phase variations in the intensity of jets, more cold air flows southward from high latitudes and converges in China. Furthermore, the anomalous anticyclonic center near the Ural Mountains and the cyclonic center to the north of China, along with the weakened polar-front jet, usually favor the frequently long-lived NW–SE UB and then brings about more intense and widespread cold events. By calculating, we found that the ASI can respectively explain 54%, 39.1%, 72.5% and 45.2% of the increased UB frequency, the slackened subpolar westerly winds, the decreased vertical shear and the enhanced East Asian subtropical westerly winds during 1998–2013. At the lower level, the widespread positive SLP belt over the northern Eurasian continent also helps the cold air from the Russian Far East blow southwestward to China. The WAF and wave ray trajectories are further employed to illustrate that the background state during the faster sea–ice loss period (1998–2013) is more favorable to the wave energy propagating from Arctic to China. In the warming period, the cold China and the circulation anomalies associated with the slower sea–ice loss are indistinctive, which implies that the ASI variability is not a crucial factor for China SAT change in this epoch.

The above results are consistent with some findings of the previous studies. There are also aspects distinguished from the earlier works. First, some scientists revealed that the combined NAO+–UB pattern (more persistent, quasi-stationary and NW–SE tilted) has a substantial influence on the amplified warming and sea–ice loss in the Barents-Kara Seas, which is also the key reason for more widespread Eurasian cold winters since 2000 (Luo et al. 2016a, b, 2017a, c; Yao et al. 2017; Gong and Luo 2017). Note that these studies emphasize the impact of UB events on the synoptic timescale. Just as important, the long-time mean sea–ice reduction also provides a background that favors the frequently persistent UB and NAO phase change. Different from the above findings, we focus on the ASI forcing on a longer (interannual and interdecadal) timescale rather than a short timescale of days or weeks. Second, Yang et al. (2018) discussed four regimes of East Asian cold events and analyzed the possible mechanisms, precursor signals and their lifetimes. But they didn’t divide different periods or demonstrate the Arctic impact on East Asian cold winters. Third, the innovation of this paper is to quantify the interdecadal and interannual contributions of ASI reduction to China SAT. From the long-term perspective, we also verified the role of ASI-related key systems (UB and westerly winds) in China warming hiatus. It helps us to intuitively understand the ASI impact on China SAT change and predict the long-term SAT variation in China.

As shown above, we quantitatively measure the contribution of ASI to China cooling trend. However, the ASI is not the only origin of the warming hiatus or the Warm Arctic–cold continents pattern. How to distinguish the contributions of the ASI, the ocean effect and other forcing factors to the warming hiatus is quite a hard issue and has not been well understood. For instance, Screen and Francis (2016) indicated that under the negative PDO phase, Arctic amplification is larger (75–150% greater warming) when the pattern and amount of sea ice reduction is the same, relative to the positive phase. The results imply that the climate response to the anomalous ASI may rely on the PDO phase, and the PDO is also regarded as one possible origin of the global warming hiatus. Note that the IPO/PDO turned from the positive phase to the negative phase around the late twentieth century (Henley et al. 2015; Newman et al. 2016). Then the negative stage shifts to the positive one around 2013 (Figure omitted). The period of positive/negative phase of IPO/PDO is consistent with the warming/hiatus epoch in our study. So, the sea–ice induced China warming hiatus may be regulated by the decadal/interdecadal cooling in the tropical Pacific. Luo et al. (2017b) also indicated that AMO+ (1999–2015) can modulate the Barents-Kara Seas warming as well as the sea–ice loss and further produce the Eurasian cold anomaly through the weakened westerly winds and NW–SE-tilted UB events. Besides, on the synoptic timescale, some studies revealed that the UB variability and NAO+ rather than ASI loss may play a more important role in the Warm Arctic–cold continents since 2000 (Luo et al. 2016a, b, 2017c). The interaction between the tropics and extratropics and their combined effects on warming hiatus are still unclear. All the above issues require further investigation.
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A link of China warming hiatus with the winter sea ice loss in Barents–Kara Seas


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