Supplementary Materials for

A stratospheric pathway linking a colder Siberia to Barents-Kara Sea sea ice loss

Pengfei Zhang*, Yutian Wu, Isla R. Simpson, Karen L. Smith, Xiangdong Zhang, Bithi De, Patrick Callaghan

*Corresponding author. Email: zpengfei@purdue.edu

DOI: 10.1126/sciadv.aat6025

This PDF file includes:

Comparison of the SIC forcing to earlier works
Calculation of EP flux
Fig. S1. SAT anomaly in each month in BKS_FL run.
Fig. S2. Polar cap geopotential height and EP flux anomalies and linear constructive interference of planetary-scale waves in BKS_FL run.
Fig. S3. Polar cap geopotential height and EP flux anomalies in BKS_TP and BKS_SP runs.
Fig. S4. Evolution of CAO and Siberian High index.
Fig. S5. Winter SAT anomaly in BKS_CAM4 run and ARC run.
Fig. S6. Comparison between CTRL and CTRL_NUDG in December.
Table S1. Description of experiments.
Reference (38)
Supplementary Materials

Comparison of the SIC forcing to earlier works
As described in the main text and Materials and Methods, the prescribed BKS SIC forcing used in this study is from the future projection in CESM-WACCM4 same as that used in (13). The September-October-November BKS SIC change is about 20%, which is comparable to the forcing magnitude (about 18%) obtained from HadISST (https://www.metoffice.gov.uk/hadobs/hadisst/) in (6) and greater than that (about 6-16%) in the AGCM runs in (7) (see the comparison with forcing in (6) in the fig. S6 in (7)). The similarity in the magnitude between the projected SIC changes used in this study and the observed SIC changes used in (6) could be attributed to, at least, two reasons: firstly, the climate models tend to under-estimated the sea ice loss (38); secondly, the observed SIC changes in (6) are the differences between two extreme groups, i.e. the 10 lowest BKS SIC years and the 10 highest years. The difference in the forcing magnitude also could be one of the reasons of the discrepancy in models results (see (17) and references therein). Furthermore, the largest SIC forcing used in the AGCM runs of (7) is located at the Chukchi Sea and the East Siberian Sea (see their fig. S6b). Sea ice perturbations in different geographical areas of the Arctic Ocean may result in different midlatitude responses (see the discussion in the main text). For the discussion here, we use the BKS region as defined in (6).

Calculation of EP flux
We use Eliassen-Palm (EP) flux to diagnose wave propagation (see fig. S2). In the quasigeostrophic approximation, EP flux is written as \( \vec{F} = \left( F_\psi, F_\phi \right) \), and \( F_\psi = -a \cos \phi \langle \psi^* \rangle \) and
\[
F_\phi = af \cos \phi \langle \theta^* \rangle, \\
\text{where } a, \ f \ \text{and} \ \phi \ \text{denote the radius of the earth, Coriolis parameter and latitude,} \\
u \text{and} \ v \ \text{are zonal and meridional velocities,} \ \theta \ \text{is potential temperature,} \ \langle \dot{\quad} \rangle \ \text{denotes zonal average,} \ \text{superscript} ^* \ \text{is deviation from zonal mean and overbar denotes time average.} \\
\text{The EP flux divergence is calculated as} \ \frac{1}{a \cos \phi} \nabla \cdot \vec{F} = \frac{1}{a \cos \phi} \left\{ \frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} \left( F_\phi \cos \phi \right) + \frac{\partial}{\partial \psi} F_\psi \right\}. \\
\text{The direction of EP flux indicates the wave propagation and the flux divergence measures the wave forcing on the zonal wind.}
Fig. S1. SAT anomaly in each month in BKS_FL run. (A to E) Same as the surface air temperature anomaly in Fig. 3A, but for November (A), December (B), January (C), February (D) and March (E), respectively.
Fig. S2. Polar cap geopotential height and EP flux anomalies and linear constructive interference of planetary-scale waves in BKS_FL run. (A) Daily evolution of the polar cap geopotential height anomalies ($Z_{pcap}$, units: gpm). (B) Eliassen-Palm (EP) flux (vectors, units: $10^{15}$ m$^3$), EP flux divergence (color shadings, units: m s$^{-1}$ day$^{-1}$) and zonal mean zonal wind (blue contours, contour interval is 0.5 m s$^{-1}$, negative values are dashed) anomalies during DJF. The EP flux is multiplied by the square root of 1000/pressure (hPa) to better demonstrate the waves activities in the stratosphere. (C) Zonal wave-1 anomaly of geopotential height (color shading, units: gpm) in the BKS_FL run and the zonal wave-1 climatology in the CTRL run (contours, the interval is 40gpm and the zero lines are omitted). (D) Same as (C) but for the zonal wave-2 component. Stippling indicates the statistical confidence at the 95% level for geopotential height and its components of zonal waves.
Fig. S3. Polar cap geopotential height and EP flux anomalies in BKS_TP and BKS_SP runs. (A and C) Same as the fig. S2A but for the BKS_TP (A) and BKS_SP (C) runs. Stippling indicates the statistical confidence at the 95% level. (B and D) Same as fig. S2B but for the BKS_TP (A) and BKS_SP (C) runs.
Fig. S4. Evolution of CAO and Siberian High index. (A) Composites of the daily evolution of Siberian SAT (lines, units: K) and its upper and lower 95% confidence limits (color shading; light gray for CTRL, pink for BKS_FL, khaki for BKS_TP and light blue for BKS_SP) for the CAO events in each experiment; (B) Same as (A) but for the Siberian High Index (SHI, units: hPa); (C) Leading EOF mode of winter SLP in the CTRL run. The Siberian High Index (SHI) is defined as the weighted area-averaged sea level pressure (SLP) over 65°-100°E and 60°-75°N, the region where the maximum in the leading EOF mode of winter SLP in the CTRL run is located (the red box in C). 5-day running averages are used in (A, B). The vertical reference line in (A, B) highlights the day (Day-0) when Siberian SAT first exceeds the CAO criterion. The EOF is calculated over 25°-85°N and 40°-140°E.
Fig. S5. **Winter SAT anomaly in BKS_CAM4 run and ARC run.** (A, B) Same as the DJF SAT anomaly in Fig. 3A (units: K), but for the BKS_CAM4 run (A) and ARC run (B). (C) Same as the Fig. 2B but for the whole Arctic sea ice changes used in the ARC run.
Fig. S6. Comparison between CTRL and CTRL_NUDG in December. (A to C) Zonal mean zonal wind (units: m s$^{-1}$) in the CTRL (A), CTRL_NUDG (B) and their difference (C). The intervals are 10 m s$^{-1}$ in (A and B) and 0.5 m s$^{-1}$ in (C). (D to F) are the same as (A to C), but for the 45°-55°N averaged zonal wave-1 component of zonal wind. The intervals are 5 m s$^{-1}$ in (D, E) and 0.5 m s$^{-1}$ in (F). The zero lines in (A to C) are omitted. Here we use the original model outputs on a hybrid-sigma vertical coordinate.
Supplementary Table S1

Table S1. Description of experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>Control run, boundary condition is repeating seasonal cycle of climatological sea ice concentration (SIC) and sea surface temperature (SST) in the historical run of CESM1-WACCM4 during 1980-1999</td>
</tr>
<tr>
<td>BKS_FL</td>
<td>Same as the CTRL run, except that the SIC and SST in the BKS region are replaced by those of the 2080-2099 period of the RCP8.5 run</td>
</tr>
<tr>
<td>BKS_TP</td>
<td>Same as the BKS_FL run, except that a nudging method is applied to the stratosphere and above, and zonal mean state is nudged towards that in the CTRL run</td>
</tr>
<tr>
<td>BSK_SP</td>
<td>Same as the CTRL run, except that a nudging method is applied to the stratosphere and above, and zonal mean state is nudged towards that in the BKS_FL run</td>
</tr>
<tr>
<td>ARC</td>
<td>Same as the BKS_FL run, except that the SIC and SST in the pan-Arctic are replaced by that in the RCP8.5 run during 2080-2099</td>
</tr>
<tr>
<td>CTRL_NUDG</td>
<td>Same as the CTRL run, except that a nudging method is applied to the stratosphere and zonal mean state is nudged towards that of the CTRL run</td>
</tr>
<tr>
<td>CTRL_CAM4</td>
<td>Same as the CTRL run, except that CAM4 is used</td>
</tr>
<tr>
<td>BKS_CAM4</td>
<td>Same as the BKS_FL run, except that CAM4 is used.</td>
</tr>
</tbody>
</table>