

## Supplementary Materials for

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

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## 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  $\vec{F} = (F_\varphi, F_p)$ , and  $F_\varphi = -a \cos \varphi \overline{\langle u^* v^* \rangle}$  and

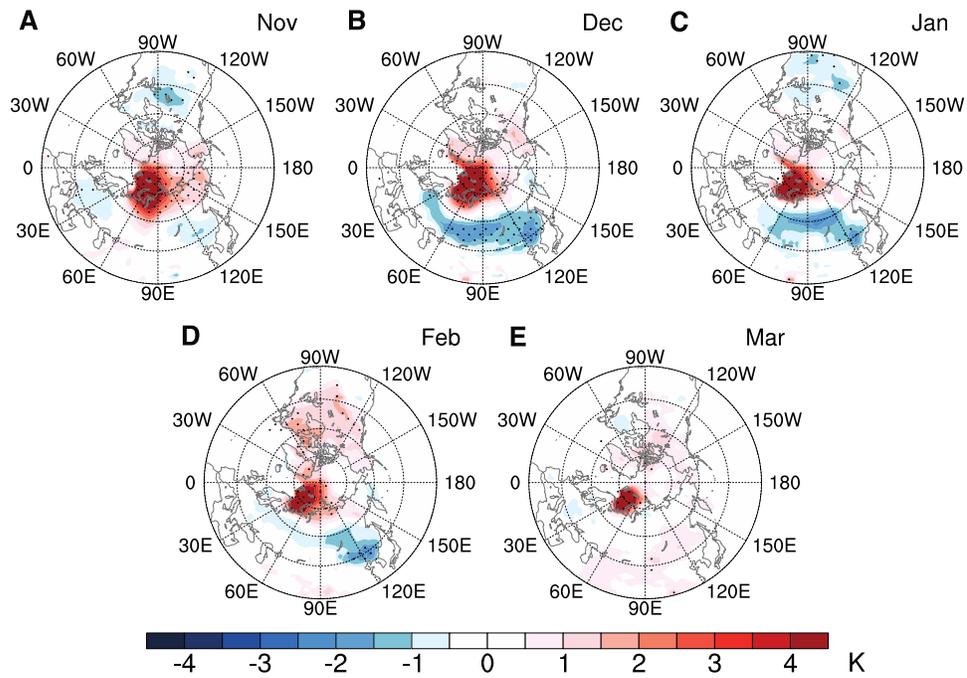
$$F_p = af \cos \varphi \frac{\overline{\langle v^* \theta^* \rangle}}{\langle \theta \rangle_p},$$
 where  $a$ ,  $f$  and  $\varphi$  denote the radius of the earth, Coriolis parameter and

latitude,  $u$  and  $v$  are zonal and meridional velocities,  $\theta$  is potential temperature,  $\langle \rangle$  denotes zonal average, superscript \* is deviation from zonal mean and overbar denotes time average. The

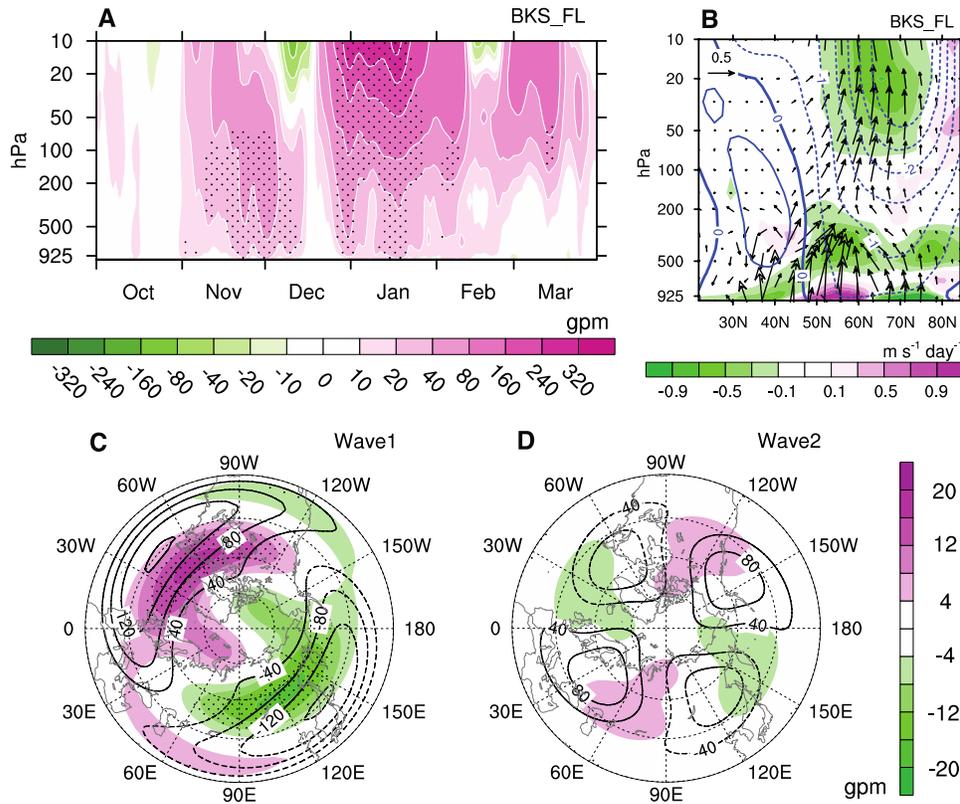
EP flux divergence is calculated as  $\frac{1}{a \cos \varphi} \nabla \cdot \vec{F} = \frac{1}{a \cos \varphi} \left\{ \frac{1}{a \cos \varphi} \frac{\partial}{\partial \varphi} (F_\varphi \cos \varphi) + \frac{\partial}{\partial P} F_p \right\}$ . The

direction of EP flux indicates the wave propagation and the flux divergence measures the wave forcing on the zonal wind.

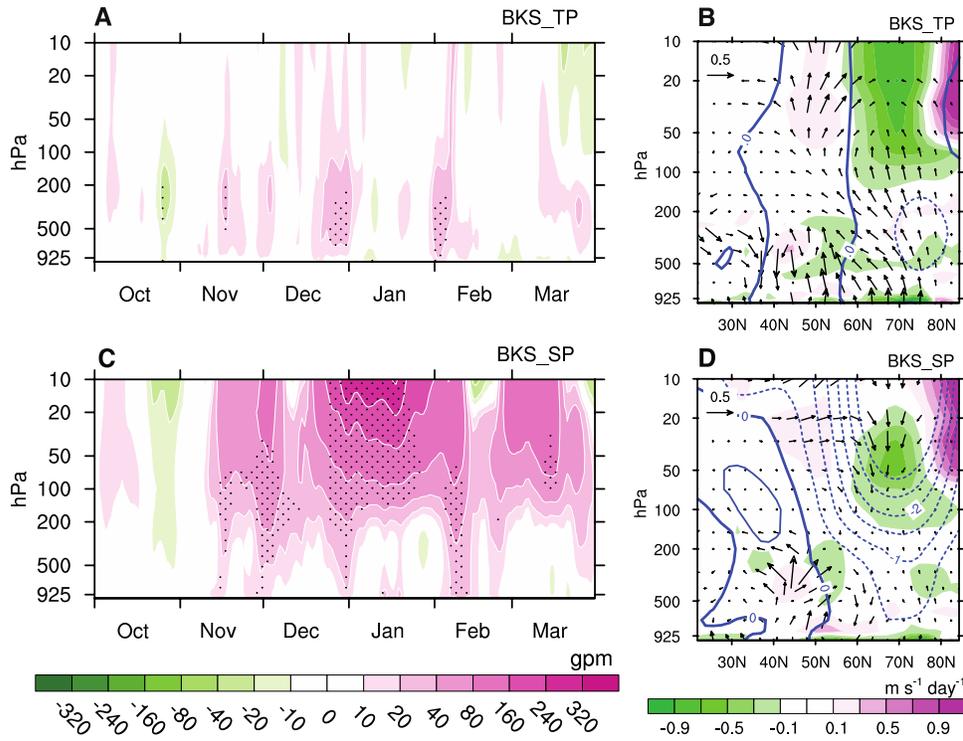
## Supplementary Figures S1-S6



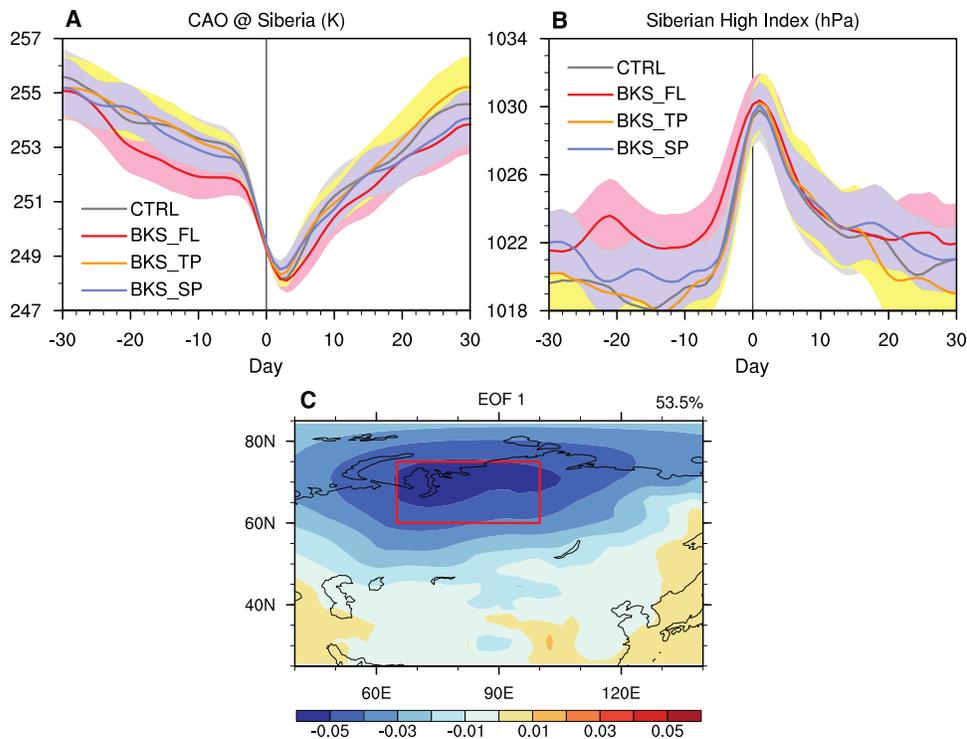
**Fig. S1. SAT anomaly in each month in BKS\_FL run. (A to E)** Same as the surface air temperature anomaly in Fig. 3A, but for November (A), December (B), January (C), February (D) and March (E), respectively.



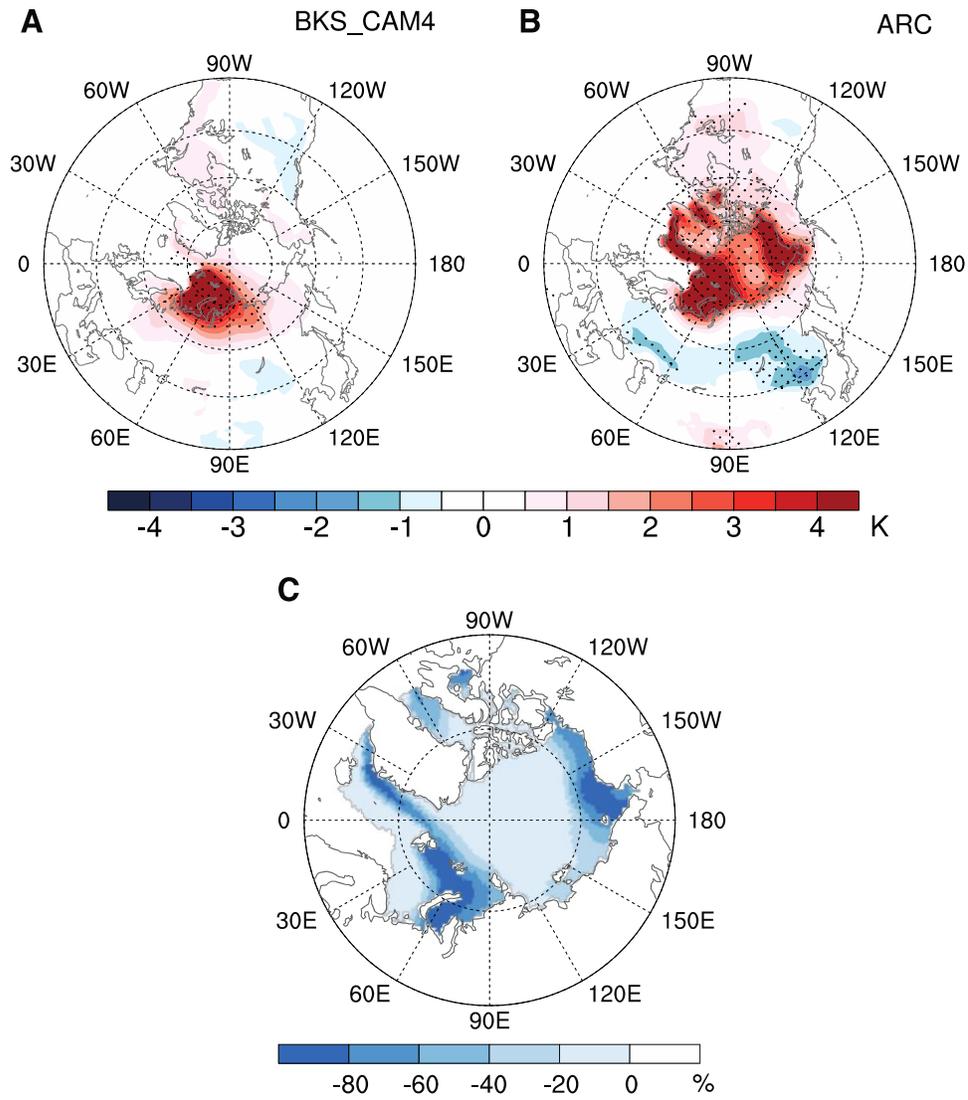
**Fig. S2. Polar cap geopotential height and EP flux anomalies and linear constructive interference of planetary-scale waves in BKS\_FL run.** (A) Daily evolution of the polar cap geopotential height anomalies ( $Z_{pcap}$ , units: gpm). (B) Eliassen-Palm (EP) flux (vectors, units:  $10^{15} \text{ m}^3$ ), EP flux divergence (color shadings, units:  $\text{m s}^{-1} \text{ day}^{-1}$ ) and zonal mean zonal wind (blue contours, contour interval is  $0.5 \text{ m s}^{-1}$ , negative values are dashed) anomalies during DJF. The EP flux is multiplied by the square root of  $1000/\text{pressure}$  (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.



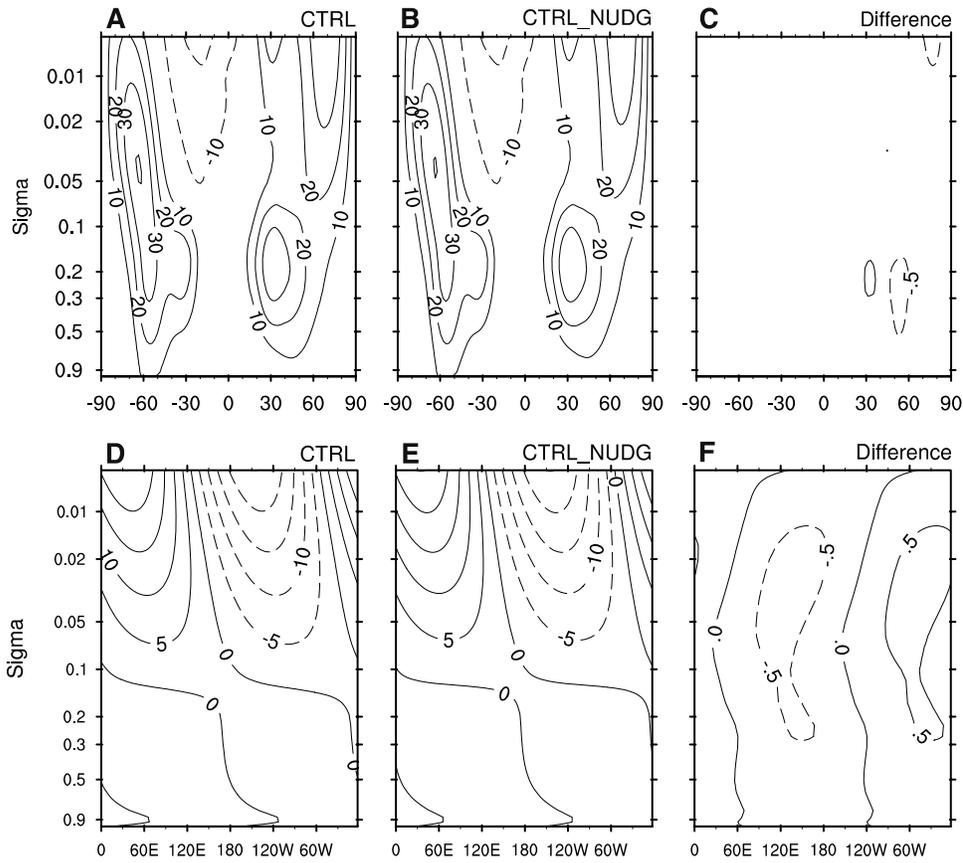
**Fig. S3. Polar cap geopotential height and EP flux anomalies in BKS\_TP and BKS\_SP runs.** (A and C) Same as the fig. S2A but for the BKS\_TP (A) and BKS\_SP (C) runs. Stippling indicates the statistical confidence at the 95% level. (B and D) Same as fig. S2B but for the BKS\_TP (A) and BKS\_SP (C) 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  $65^{\circ}$  -  $100^{\circ}$  E and  $60^{\circ}$  -  $75^{\circ}$  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  $25^{\circ}$  -  $85^{\circ}$  N and  $40^{\circ}$  -  $140^{\circ}$  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:  $\text{m s}^{-1}$ ) in the CTRL (A), CTRL\_NUDG (B) and their difference (C). The intervals are  $10 \text{ m s}^{-1}$  in (A and B) and  $0.5 \text{ m s}^{-1}$  in (C). (D to F) are the same as (A to C), but for the  $45^\circ\text{-}55^\circ\text{N}$  averaged zonal wave-1 component of zonal wind. The intervals are  $5 \text{ m s}^{-1}$  in (D, E) and  $0.5 \text{ m s}^{-1}$  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.**

Experiment	Description
CTRL	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
BKS_FL	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
BKS_TP	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
BSK_SP	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
ARC	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
CTRL_NUDG	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
CTRL_CAM4	Same as the CTRL run, except that CAM4 is used
BKS_CAM4	Same as the BKS_FL run, except that CAM4 is used.