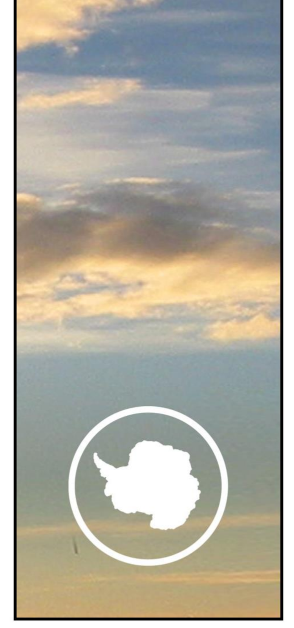
The influence of regional Arctic sea-ice loss on the stratosphere, and mid-latitude weather and climate



Christine McKenna [a,b,*], Tom Bracegirdle [a], Emily Shuckburgh [a], and Peter Haynes [b]

[a] British Antarctic Survey, Cambridge, UK
[b] Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK
* Email: *christine.mckenna@bas.ac.uk*

1. Context

The spatial pattern of Arctic sea-ice loss varies year to year (Fig. 1.1) and is very uncertain in projections. Thus, it is important that we understand the different mid-latitude impacts of different regions of sea-ice loss and the mechanisms involved. Decomposing sea-ice loss into regions may also make it easier to understand the response to pan-Arctic anomalies.

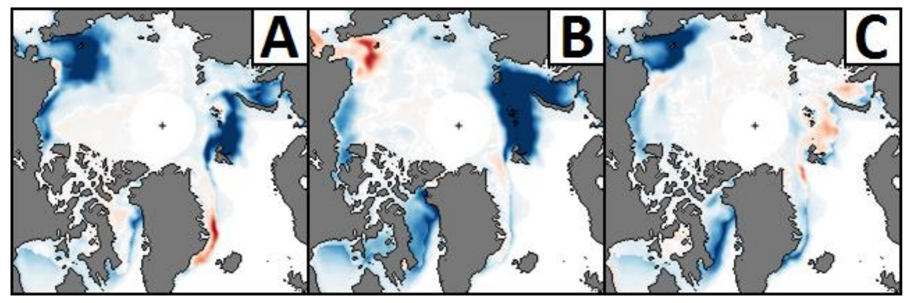


Fig. 1.1: Sea-ice concentration (%) anomalies in Nov **(A)** 2007, **(B)** 2012, and **(C)** 2014. Blue is negative, red is positive. Source: *NSIDC.*

2. Stratospheric-tropospheric mechanisms

- Sun et al. (2015) find that sea-ice loss in the Atlantic/Pacific sector of the Arctic weakens/strengthens the stratospheric polar vortex (Fig. 2.1).
- A weaker/stronger vortex is often followed by a more negative/positive AO/NAO (Arctic Oscillation/North Atlantic Oscillation)[1] and, thus, colder/warmer weather conditions in mid-latitude regions.
- The weakening/strengthening of the vortex is due to enhanced/suppressed forcing of upward propagating Rossby waves (Fig. 2.2). This occurs because of constructive/destructive linear interference between anomalous and climatological waves.

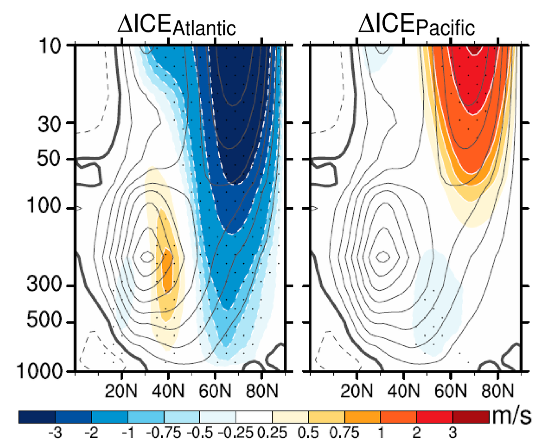


Fig. 2.1[2]: Response of Dec-Feb zonal mean zonal wind [U] to projected late 21st century sea-ice loss in the Atlantic & Pacific sectors of Arctic. Contours: control run climatology.

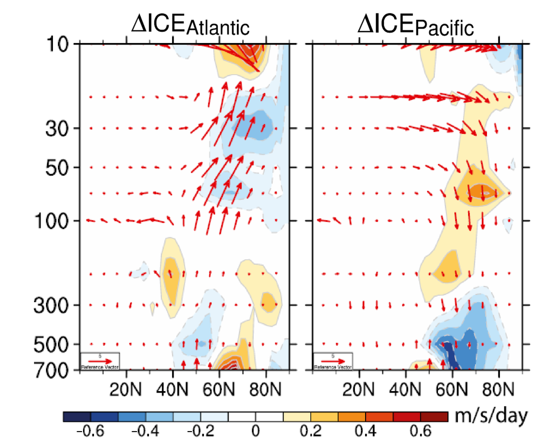


Fig. 2.2[2]: Response of Dec-Jan EP flux (arrows, shows direction of wave propagation) & EP flux divergence (shading, shows of forcing on [U] by waves).

3. Research questions

- Do Atlantic and Pacific sector sea-ice loss have different mid-latitude impacts, and is the stratosphere key? What is the combined impact of these regions of sea-ice loss?
- To answer these questions we use IGCM4[3], an intermediate complexity climate model (Box 1).

Box 1: Numerical model - IGCM4

- Has a well resolved stratosphere: model lid at 0.1 hPa, 13 out of 35 model levels in stratosphere.
- Allows long simulations, but still represents complex dynamics well (e.g. stratospheric processes).
- Parameterises the effects of sea-ice (albedo, roughness, heat capacity) through the SST field.

4. Experiments

- 200 years long
- Atmosphere only mode
- **Control run (CTL)**: impose annually repeating cycle of historical mean surface conditions (using ERA-interim data).
- **3 sea-ice loss runs**: same as CTL, but add an annually repeating cycle of surf. temp. anomalies in the (1) Atlantic sector (Barents-Kara Seas – **BAKA run**), (2) Pacific sector (Chukchi-Bering Seas – **CHUBER run**), & (3) both sectors **(BAKA&CHUBER run)** (Fig. 4.1).

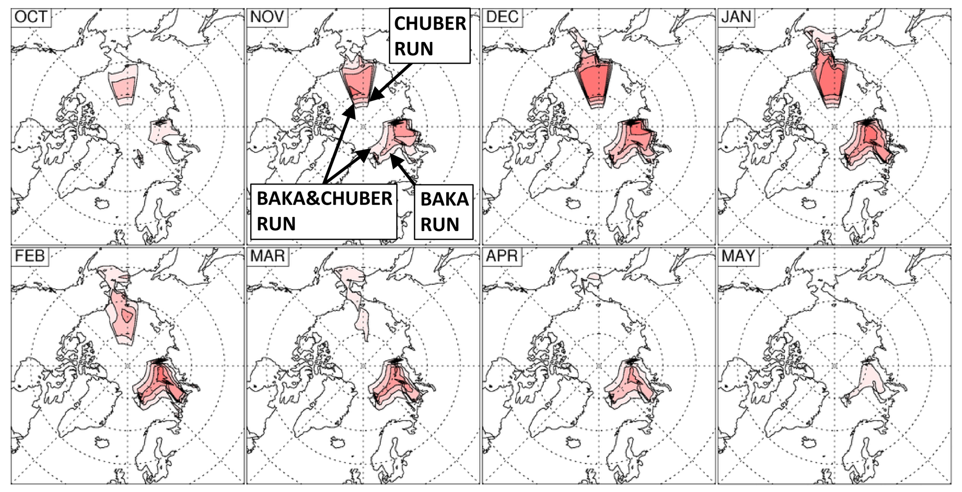


Fig. 4.1: Surface temp (Ts) anomalies used in the Atlantic, Pacific, and combined sea-ice loss runs (BAKA, CHUBER and BAKA&CHUBER) (contour interval of 5°C). Derived using HadGEM2-ES RCP8.5 projections of sea-ice for 2070-99: where there is 100% loss in future, bring Ts to 0°C; 50% loss → bring Ts halfway to 0°C (etc).

5. Results: Atlantic versus Pacific sea-ice loss

Figure 5.1: Key meteorological fields

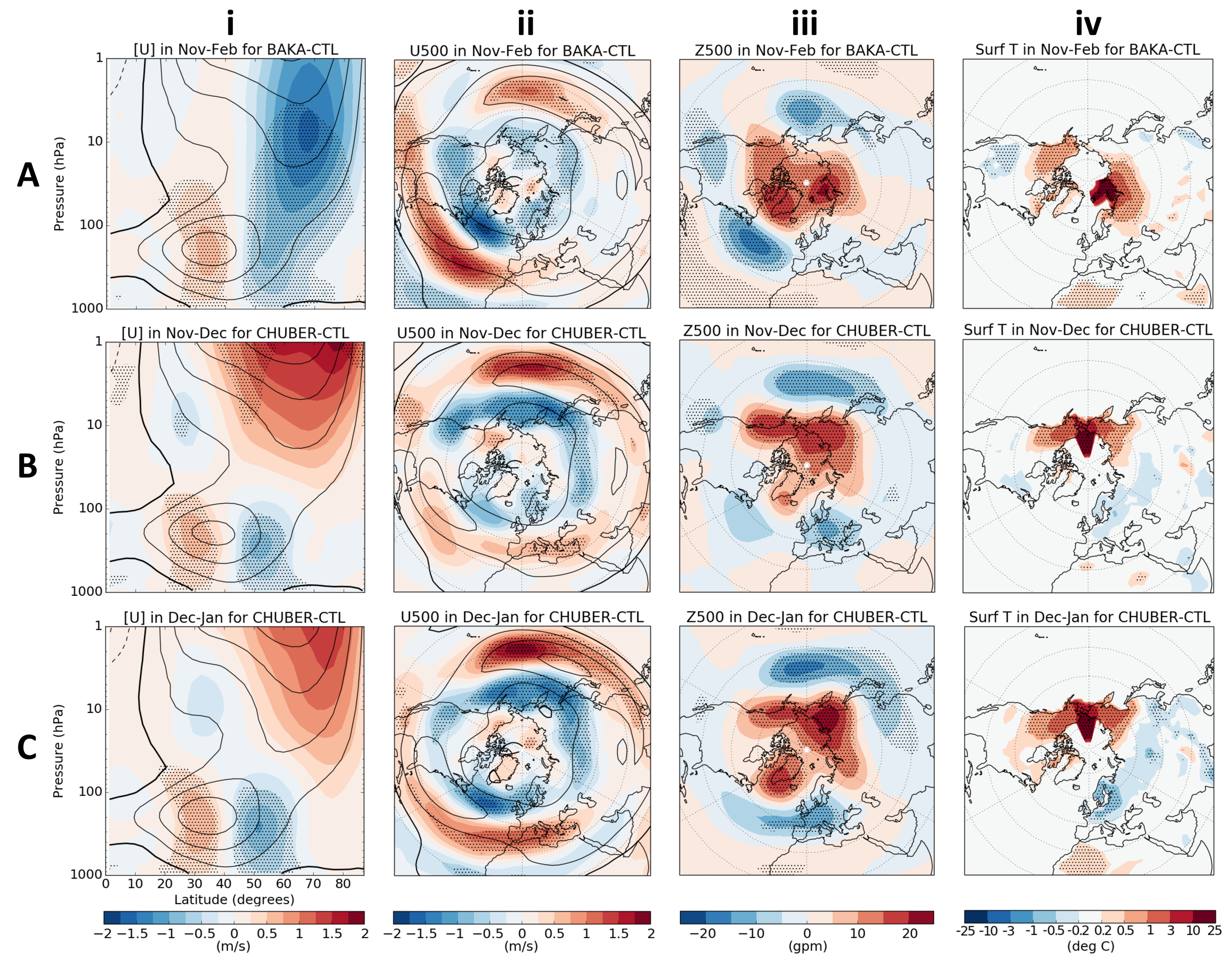


Fig. 5.1: Response of various fields to future sea-ice loss in the Atlantic/Pacific sectors of the Arctic (BAKA/CHUBER runs). **(i)** zonal mean zonal wind [U], **(ii)** U at 500 hPa, **(iii)** geopotential height Z at 500 hPa, & **(iv)** surface temperature T in **(A)** BAKA Nov-Feb, **(B)** CHUBER Nov-Dec, & **(C)** CHUBER Dec-Jan. Contours: climatology from control run (CTL), interval of 10 m/s. Stipples: significant.

Stratospheric response

- For Atlantic/Pacific sector sea-ice loss (BAKA/CHUBER runs), the vortex weakens/ strengthens in Nov-Feb/Nov-Dec (Fig. 5.1i; cf. Fig. 2.1).
- This is because upward Rossby wave propagation is enhanced/suppressed, due to constructive/destructive linear interference between wave-1 waves (Fig. 5.2; cf. Fig. 2.2).
- However, non-linear wave interference is also large in both runs (Fig. 5.3). This is of the same sign as the linear part in BAKA, but not CHUBER. This may help to explain the limited strengthening of the vortex in CHUBER.

Tropospheric response

- In the troposphere there is a negative AO/NAO pattern in Nov-Feb in BAKA & Nov-Jan in CHUBER (Fig. 5.1ii,iii).
- This implies little influence of the stratosphere on the tropospheric response in CHUBER, & perhaps BAKA.
- The negative AO/NAO only causes surface cooling in Northern Europe in CHUBER (Fig. 5.1iv). This is likely due to the proximity of the imposed surface temperature anomalies to Northern Europe in BAKA, which through warm advection counteracts dynamical cooling.

Figure 5.2: EP flux and linear wave interference

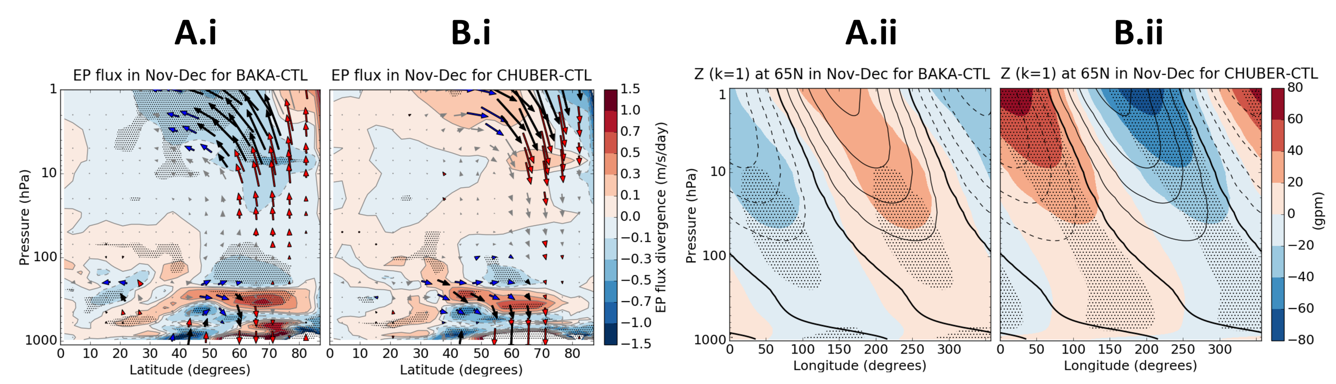


Fig. 5.2: Response of Nov-Dec **(i)** EP flux & **(ii)** wave-1 geopotential height (Z) at 65°N to future sea-ice loss in the **(A)/(B)** Atlantic/Pacific sectors of the Arctic (BAKA/CHUBER runs). Contours: climatology from control run (CTL), interval of 150 gpm. Stipples: significant. Blue/red/black arrows: significant in y/z/both directions.

Figure 5.3: Linear vs. nonlinear wave interference

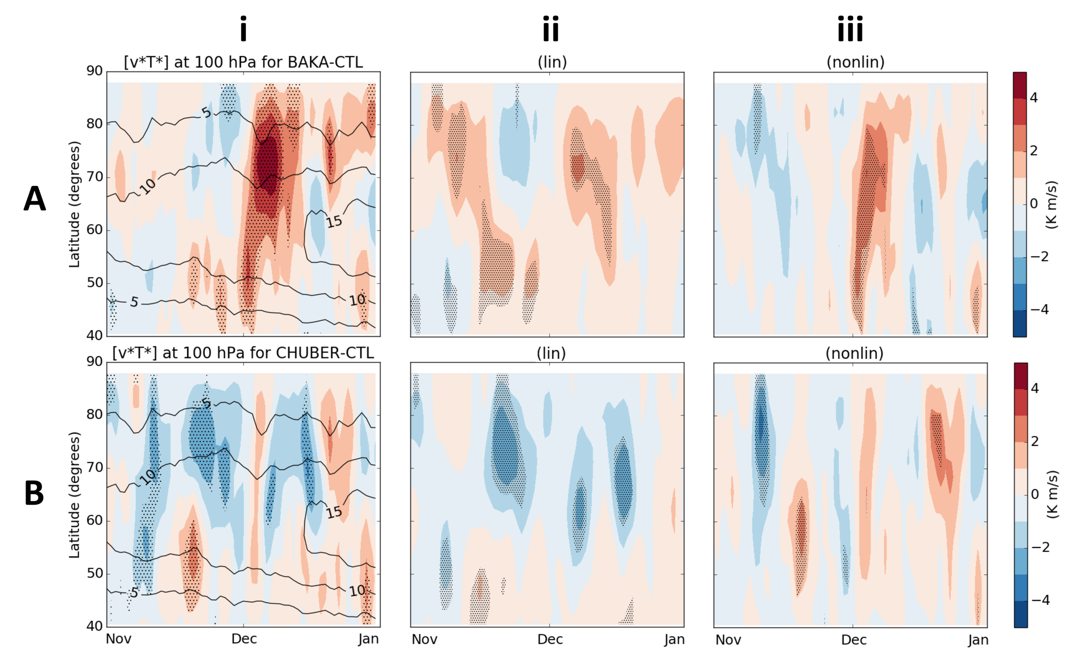


Fig. 5.3: Evolution of the zonal mean eddy heat flux response to future sea-ice loss in the **(A)/(B)** Atlantic/Pacific sectors of the Arctic (BAKA/CHUBER runs). **(i)** Full response, **(ii)** linear, & **(iii)** nonlinear parts. Contours: control run (CTL) climatology, Stipples: significant.

6. Results: combined Atlantic and Pacific sea-ice loss

- For zonal mean zonal wind [U] and surface temp., the Nov-Feb response to combined Atlantic & Pacific sector sea-ice loss (BAKA&CHUBER run) is a linear addition of the separate BAKA and CHUBER responses (Fig. 6.1i,iv).
- In U & geopotential height Z at 500 hPa, the negative AO/NAO pattern is weaker for BAKA&CHUBER than for BAKA+CHUBER (Fig. 6.1ii,iii) ⇒ nonlinear.

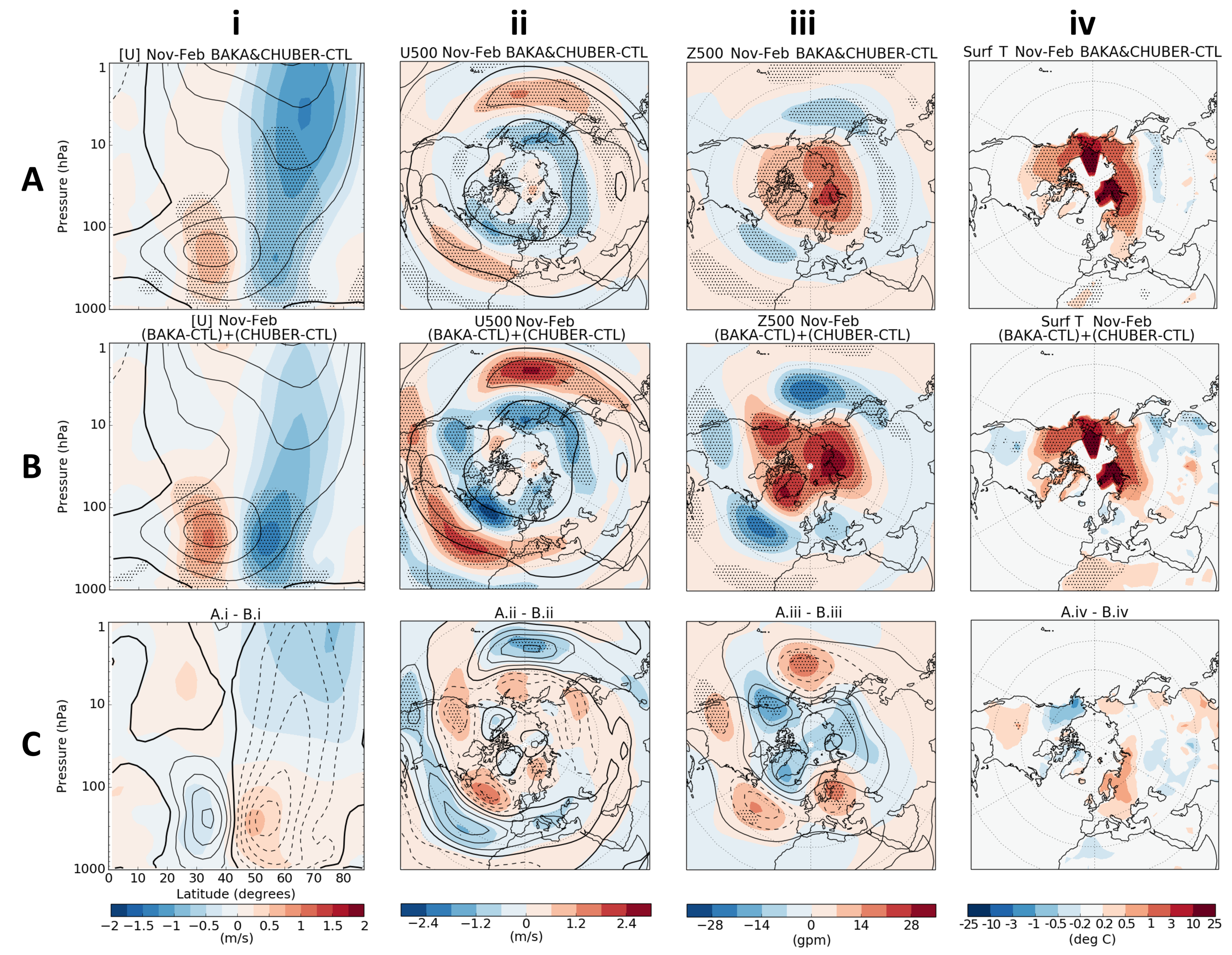


Fig. 6.1: (A) Response of various fields (as in Fig. 5.1) in Nov-Feb to future sea-ice loss in both the Atlantic & Pacific sectors of the Arctic (BAKA&CHUBER run). For comparison, **(B)** a linear addition of the separate BAKA and CHUBER responses, & **(C)** (A) minus (B). Contours: (A) & (B) - control run (CTL) climatology, interval of 10 m/s; (C) - same as shading in (B), interval as in colorbar. Stipples: significant.

7. Future research

- In another set of runs, we will relax the stratospheric zonal wind to its zonal mean climatology. This will help to quantify the role that the stratosphere played in the original runs.
- We could use a stationary wave model to look at the tropospheric mechanisms involved in the negative AO/NAO response.

8. Summary

- Atlantic/Pacific (BAKA/CHUBER) sea-ice loss weakens/strengthens the polar vortex, but results in a tropospheric negative AO/NAO in both cases. This implies little stratospheric influence.
- Surface cooling occurs in Northern Europe in CHUBER only & not in BAKA. In BAKA, thermodynamic warming counteracts dynamical cooling.
- Hence, tropospheric mechanisms explain the different impacts of Atlantic & Pacific sector sea-ice loss.
- Response to Atlantic & Pacific sea-ice loss combined is not a linear addition of the BAKA and CHUBER responses.

Acknowledgments
The authors thank Manoj Joshi (University of East Anglia, UK) for providing the IGCM4 code and setting up the model.

References

1. Baldwin, M. P., & Dunkerton, T. J. (2001). Stratospheric harbingers of anomalous weather regimes. *Science*, *294*, 581-584.
2. Sun, L., Deser, C., & Tomas, R. A. (2015). Mechanisms of Stratospheric and Tropospheric Circulation Response to Projected Arctic Sea Ice Loss. *J. Climate*, *28*, 7824-7845.
3. Joshi, M., Stringer, M., Wiel, K., O'Callaghan, A., & Fueglistaler, S. (2015). IGCM4: a fast, parallel and flexible intermediate climate model. *Geosci. Model Dev.*, *8*, 1157-1167.