The atmospheric response to extratropical ocean warming induced by Arctic sea ice loss

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Introduction

Most modelling studies that examine the impacts of sea ice loss force an atmospheric general circulation model (AGCM) with prescribed, reduced sea ice concentration while keeping sea surface temperatures (SSTs) fixed (e.g Deser et al. 2010). More recent work that studies the impact of dynamic and thermodynamic coupling to the ocean (Deser et al. 2016) finds that ocean coupling enhances warming in the Arctic mid-troposphere and tropical upper-troposphere along with amplifying the atmospheric circulation response. However the mechanisms for why the circulation response is amplified is not fully understood. In this study, we hypothesize that the extratropical ocean warming caused by sea ice loss itself is part of a positive feedback loop that amplifies the atmospheric circulation response through Arctic mid-troposphere warming. This is tested by first estimating the extratropical SST response associated with sea ice loss from coupled model experiments and then comparing AGCM experiments where sea ice loss is prescribed both with and without this sea ice loss induced ocean warming.

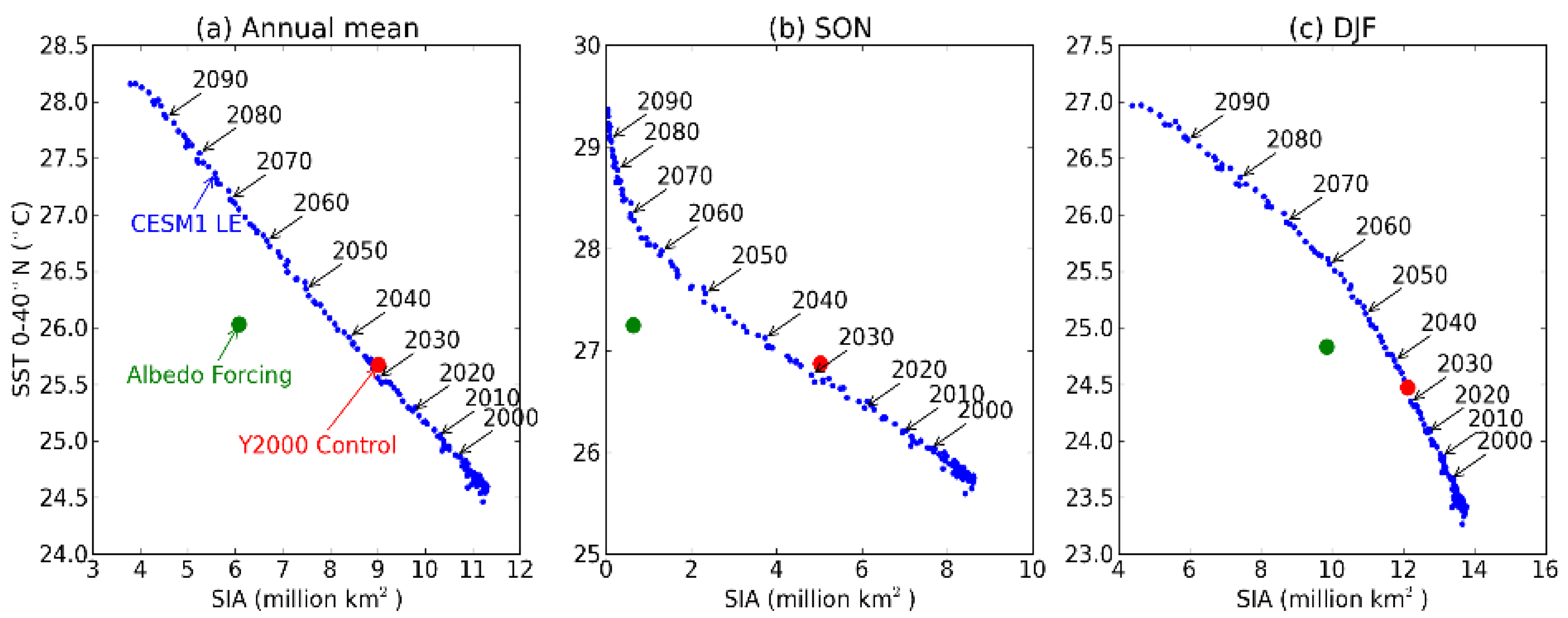


FIG. 1 : Results from CESM1 coupled model simulations. Northern Hemisphere sea ice area versus SST (°C) averaged from 0° and 40° N for the annual mean (a), the SON mean (b), and the DJF mean (c). Each blue dot represents the ensemble mean from one year of the CESM1 large ensemble historical and RCP8.5 forcing simulations. The red and green dots represent the equilibrium mean year 2000 control simulation and sea ice albedo forcing simulation respectively (Blackport and Kushner 2017).

Coupled climate model experiments

We use 1) 30 members of the CESM1 Large Initial Condition Ensemble (Kay et al. 2015) forced by historical and RCP8.5 forcing from 1920-2100 and 2) two multicentennial coupled simulations to study sea ice loss (Blackport and Kushner 2017). The Blackport and Kushner simulations consist of a constant Year 2000 radiative forcing simulation and a perturbation simulation in which the Year 2000 run's sea ice albedo is reduced to drive sea ice loss. The Large Ensemble and the sea ice perturbation simulations drive sea ice loss and low-latitude warming, however the low-latitude warming in the simulation driven by sea ice albedo forcing is significantly smaller (Fig. 1).

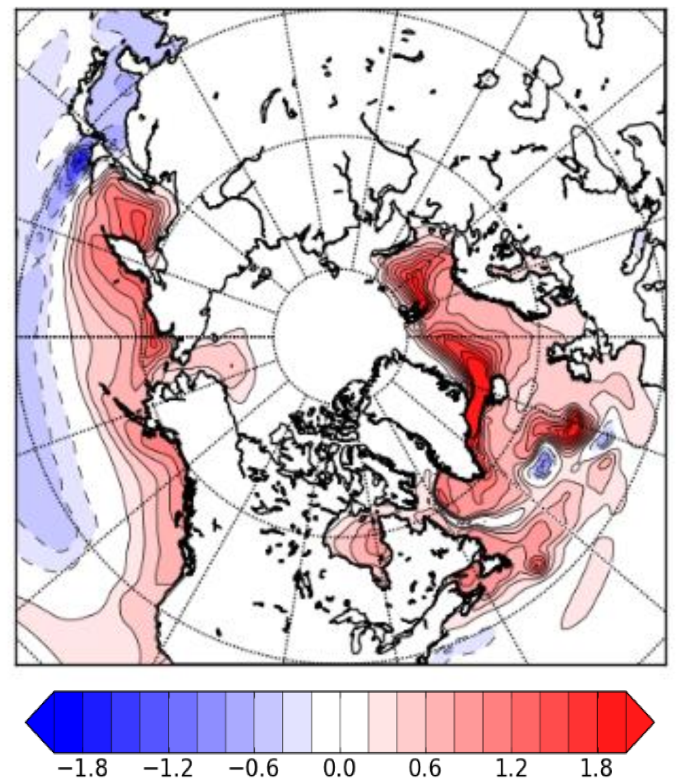
Using pattern scaling to calculate the SST response associated with sea ice loss

To isolate the part of the SST response that is associated with a reduction in sea ice area (SIA) in the absence any low-latitude warming (and vice versa) we use a two parameter pattern scaling estimate (Blackport and Kushner 2017). For each coupled climate model experiment, we can breakdown the SST response (*δSST*) into a part related to a change in low latitude (0°-40°N) SST (*δT*) and a part that is related to a change intotal Arctic SIA (*δI*) :

$$\delta SST_R = \left.\frac{\partial SST}{\partial T}\right|_I \delta T_R + \left.\frac{\partial SST}{\partial I}\right|_T \delta I_R \qquad \text{Eq. (1)}$$

$$\delta SST_A = \left.\frac{\partial SST}{\partial T}\right|_I \delta T_A + \left.\frac{\partial SST}{\partial I}\right|_T \delta I_A \qquad \text{Eq. (2)}$$

The R (A) subscript represents the RCP8.5 forcing (sea ice albedo) experiment. We calculate *δSST*, *δT* and *δI* from the simulations. The relative magnitude of *δT* and *δI* are different in each experiment, so we can solve for the two partial derivatives, which are the quantities of interest here.



Using the procedure for estimating the partial derivatives, we estimate the DJF SST response associated with sea ice loss while keeping low-latitude warming constant (i.e. the second term on the right hand side of Eq. 1) (Fig 2). The pattern consists of warming in the Arctic and Sub-Arctic extending into the midlatitude east Pacific, along with cooling in the midlatitude west Pacific which is likely dynamically induced.

FIG. 2: The part of the DJF SST response (°C) associated with sea ice loss estimated using pattern scaling (i.e. the second term on the right hand side of Eq. 1) . For the RCP8.5 experiment, the response is defined to be the difference between the 10-year mean of the epochs 2057:2066 and 2027:2036 (Blackport and Kushner 2017).

AGCM experiment design

The SST pattern in Fig. 2 becomes a driver for new AGCM simulations with the Community Atmosphere Model version 5 (CAM5) coupled to the Community Land Model version 4 (CLM4), run at approximately 1° horizontal resolution.

- Control simulation: CESM1 Large Ensemble sea ice concentration and thickness (SIC/SIT), 2027:2036 timeslice conditions for 100 years.
- "I_{RCP}": Control simulation but with SIC and SIT from 2057:2066.
- "$I_{RCP}\_T_{SIL}$": I_{RCP} but with extratropical SST derived above (as in Fig. 2).

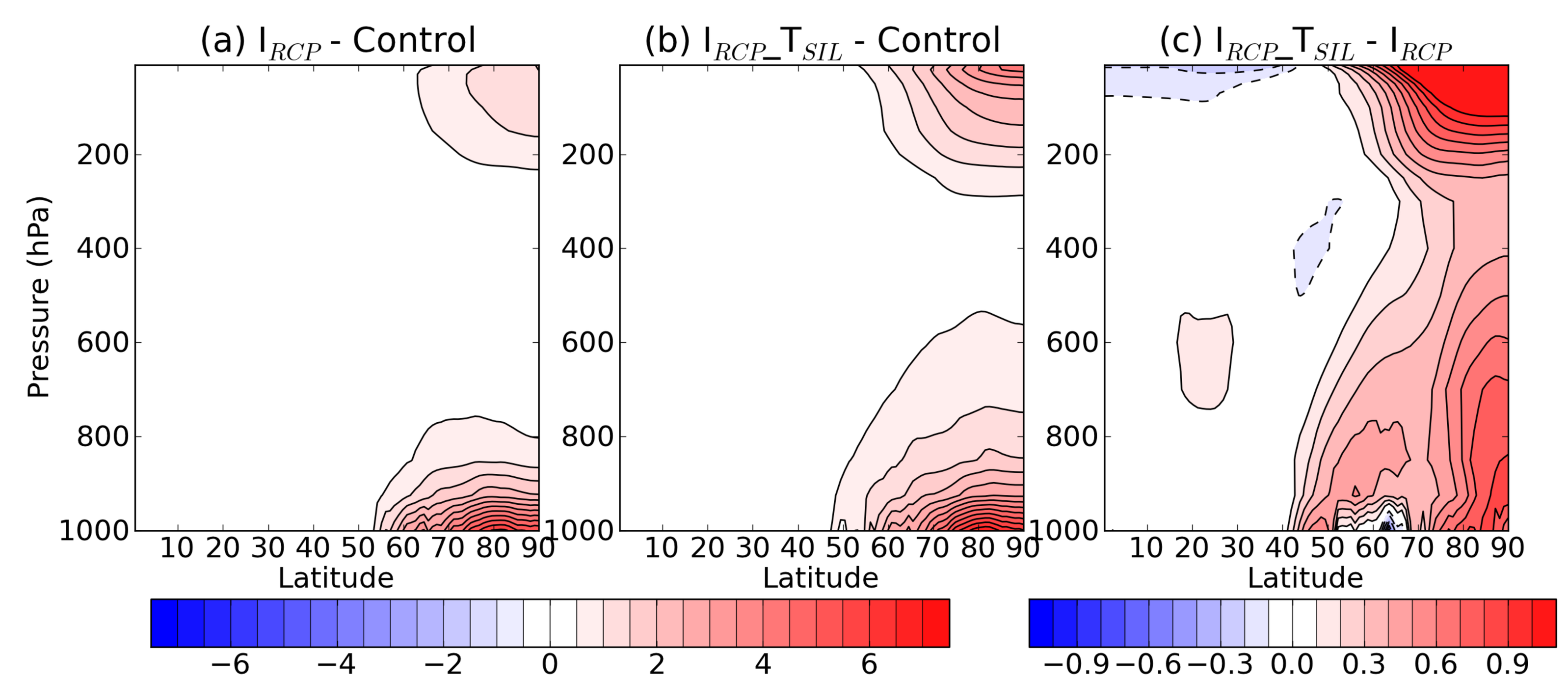


FIG. 3: The DJF zonal mean temperature (°C) response for (a) the I_{RCP} simulation (sea ice loss only), (b) the $I_{RCP}\_T_{SIL}$ simulation (sea ice loss and the extratropical SST change associated with sea ice loss), and (c) the difference between (b) and (a).

Key point: The Arctic is influenced by sea-ice induced ocean warming at lower latitudes

In response to sea ice loss only (no changes SST changes), the wintertime warming remains trapped in the Arctic lower-troposphere (Fig 3a). When the extratropical SST changes associated with sea ice loss are also prescribed, the warming extends higher into the Arctic mid-troposphere (Fig 3b). The difference between the two show that the extra warming caused by the SSTs changes associated with sea ice loss is not trapped in the lower troposphere.

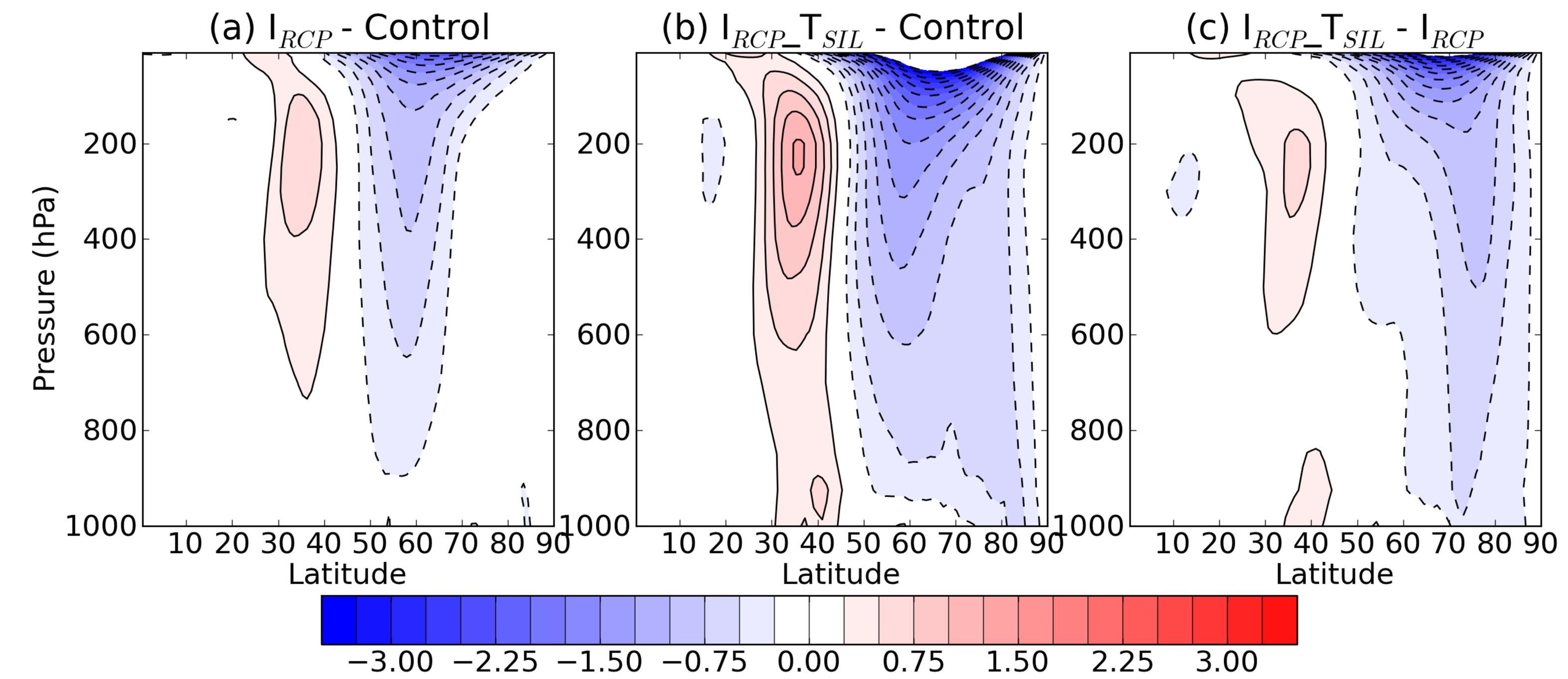


FIG. 4: As in Fig 3 but for zonal wind (m/s).

This point applies to atmospheric winds and circulation

In response to sea ice loss only, the wintertime zonal mean zonal wind response shows a weakening and southward shift the eddy driven jet (Fig 4a), similar to previous studies. When the extratropical SST forcing is included, the pattern of the response remains similar, but the magnitude is increased (Fig 4b). In Fig 4c, it can be seen that the spatial pattern and magnitude of the response due to the extratropical SST change associated with sea ice loss is similar to that of the sea ice loss itself. This amplification of the atmospheric circulation response by the SST change associated with sea ice loss is also seen in the sea level pressure (SLP) response (Fig 5).

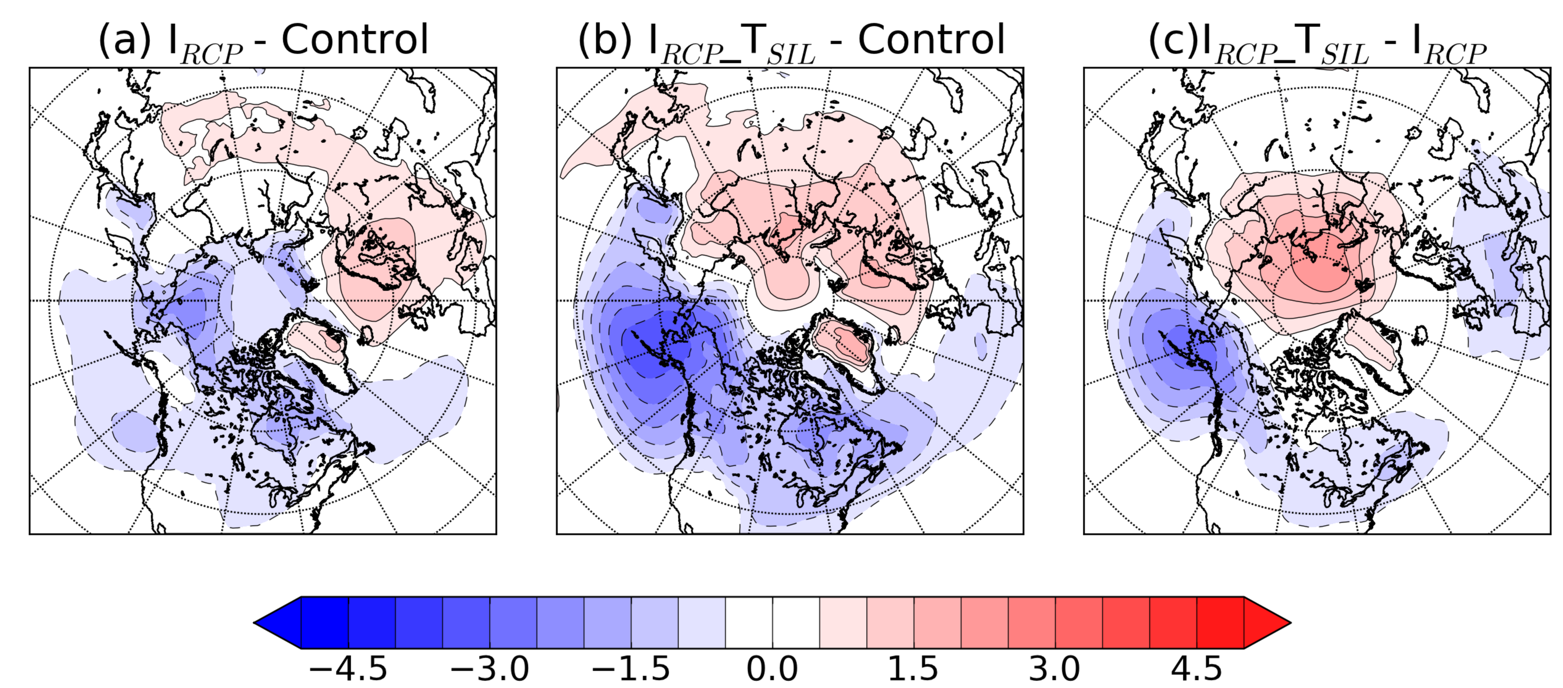


FIG. 5: As in Fig 3 but for SLP (hPa).

Conclusions

Using output from coupled climate model experiments forced separately by greenhouse gas dominated radiative forcing and sea ice albedo forcing, we have estimated the extratropical SST response associated with Arctic sea ice loss. Using an AGCM that was driven by sea ice loss, both with and without this SST pattern, we have shown that sea ice loss induced ocean warming acts to enhance Arctic mid-tropospheric warming and amplify the atmospheric circulation response. This suggests that coupling to the ocean is important and that AGCM sea ice loss experiments may underestimate the impacts on the atmospheric circulation, in agreement with Deser et al. (2016). We find, however, that in contrast to Deser et al (2016), we see these impacts without the influence of tropical warming.

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