Weakening of the storm tracks driven by ocean-atmosphere coupling

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Abstract

To determine the mechanisms driving the competing changes in the storm tracks, we use a hierarchy of models with different levels of ocean-atmosphere coupling, using forcings from the Polar Amplification Model Intercomparison Project[1] (PAMIP) to assess the role of Arctic sea ice loss on the Northern Hemisphere storm tracks. We find that ocean-atmosphere coupling is necessary to capture the weakening of the storm tracks in response to Arctic sea ice loss, that surface turbulent heat flux modulates the intensity of the weakening, and that ocean dynamics controls the meridional location of the response. A moist isentropic diagnostic of the atmospheric overturning circulation shows that most of the weakening of the storm tracks and its associated changes in atmospheric heat transport (AHT) arise from a weakening of the transient eddy mass flux.

Sea ice loss experiments

- Sea ice is artificially controlled in the coupled simulations with a hybrid nudging method[2] (see Figure 1) that directly removes or adds sea ice area and controls the thickness through a *ghost* heat flux[3].
- Sea ice concentration (SIC) and thickness (SIT) are nudged (or prescribed) to the same states following the PAMIP forcings.

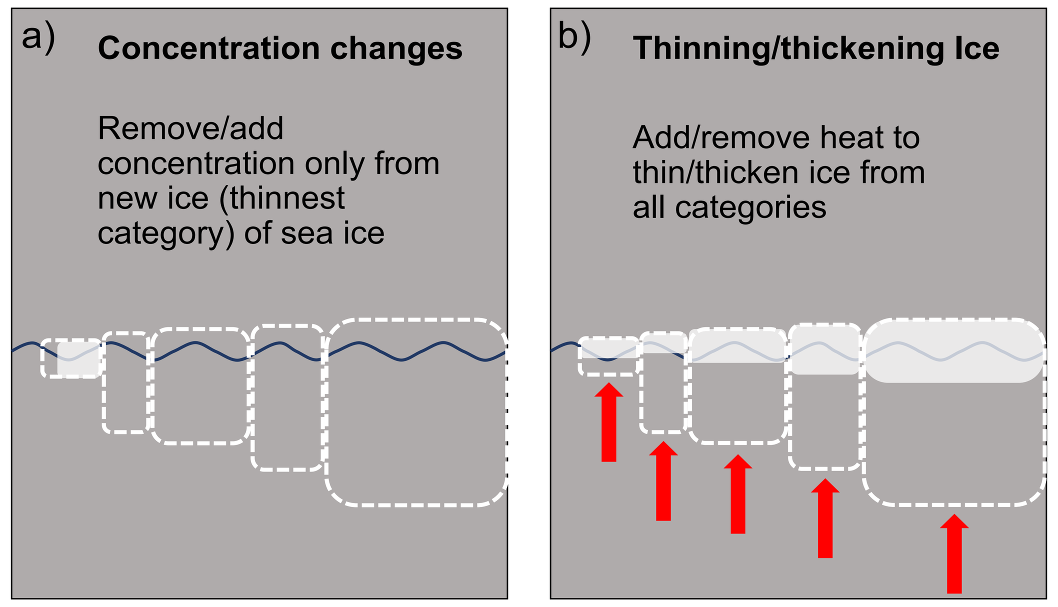

Figure 1. Schematic of nudging methodology for (a) SIC nudging and (b) SIT nudging via addition of a basal heat flux. Sea ice before nudging is represented by the white dash contour and sea ice after nudging is represented by the white shading. The red arrows represent the heat flux (measured in W/m2) applied to the bottom of the ice.

- As the complexity of ocean-atmosphere coupling increases, the sea surface temperature (SST) warming extends further South and increases intensity.
- In particular, the "fully-coupled" SST response is particularly strong in the North Atlantic. This warming signal arises after about 50 years into the integration from being advected from the Denmark Strait first by the Greenland current then the Labrador current.

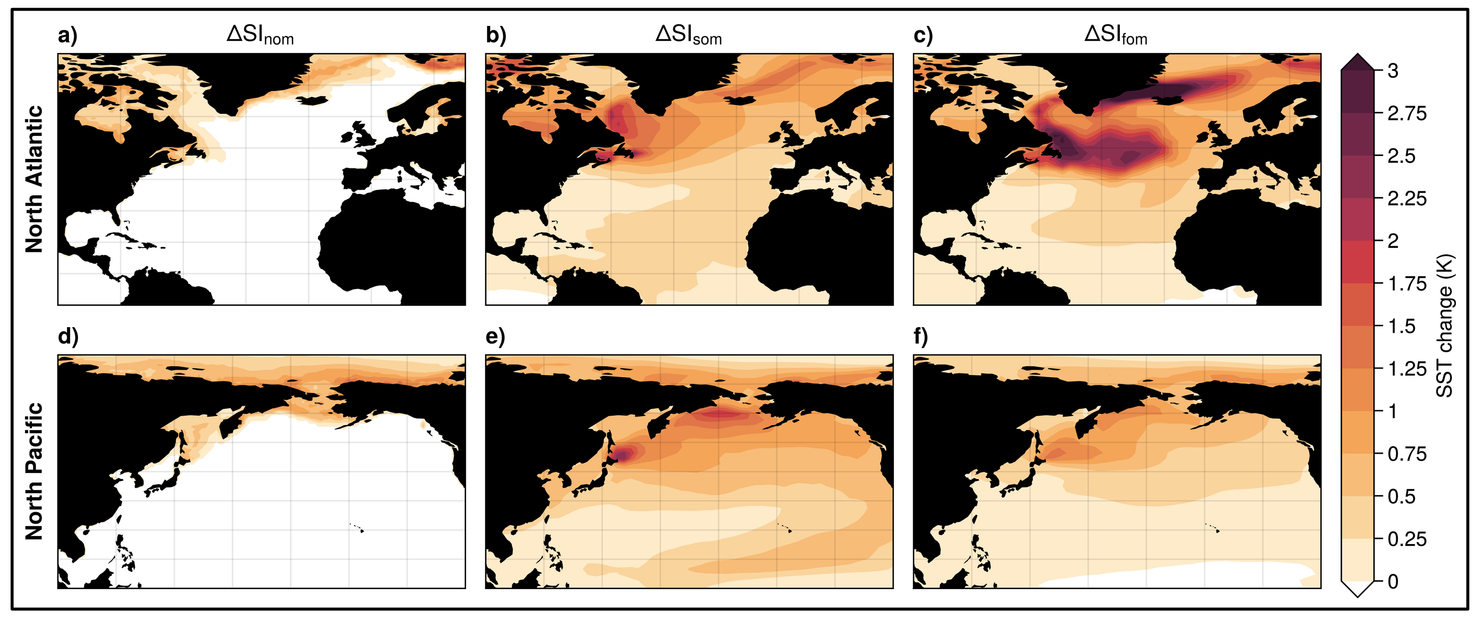

Figure 2. Annual mean SST forcings and responses. (a) North Atlantic SST forcing in the NOM simulation. (b) SST response to sea ice loss in the SOM simulations. (c) As in (b) but for the FOM simulations. (d)-(f) As in (a)-(c) but for the North Pacific.

Contribution of ocean-atmosphere coupling complexity

- The transient eddy moist static energy (MSE) flux weakens significantly over the North Atlantic. Most of this signal arises from ocean-atmosphere-coupling (Figure 3b).
- Thermodynamic coupling (Slab Ocean Model) modulates the intensity of the response to Arctic sea ice loss through a wide reduction in eddy MSE flux across the whole North Atlantic basin (Figure 3c).
- Ocean dynamics (Full Ocean Model) dictate the meridional location and extent of the signal with a significant dipole pattern in the North Atlantic storm tracks.

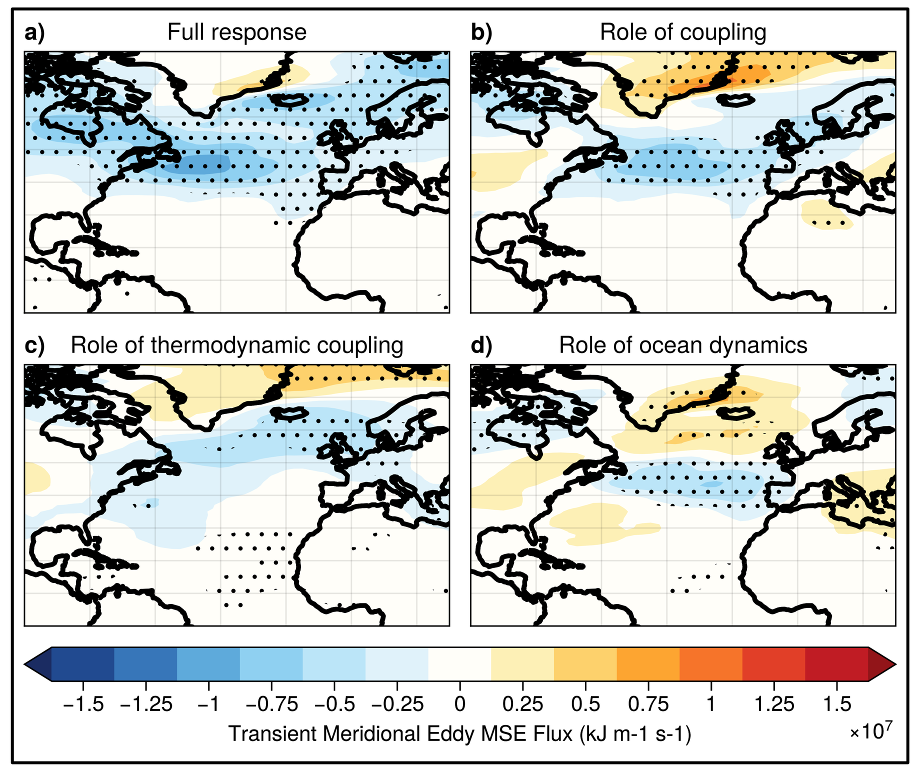

Figure 3. (a) The vertically integrated transient meridional MSE flux response to Arctic sea ice loss in FOM. (b) The relative contribution from ocean coupling (difference between FOM and NOM). (c) The contribution of thermodynamic coupling (difference between SOM and NOM). (d) The contribution of ocean circulation changes (difference between FOM and SOM). Panel (b) is equal to the sum of panels (c) and (d).

Dynamically and thermodynamically driven changes

- Using a moist isentropic representation of the atmospheric circulation, we decompose the atmospheric heat transport response into a component related to mass transport changes and one to an effective moist stratification change.

$$AHT = F(h_+ - h_-)$$
$$\Delta AHT = \Delta F\,(h_+ - h_-) + F\Delta h_+ - F\Delta h_-$$

- At high latitudes, the reduction in AHT stems from a weakening of the effective stratification, arising from a warming of the equatorward branch of the circulation.
- When an interactive ocean model is introduced, the transient eddies start to weaken in intensity in the midlatitudes, expanding the AHT reduction southward.

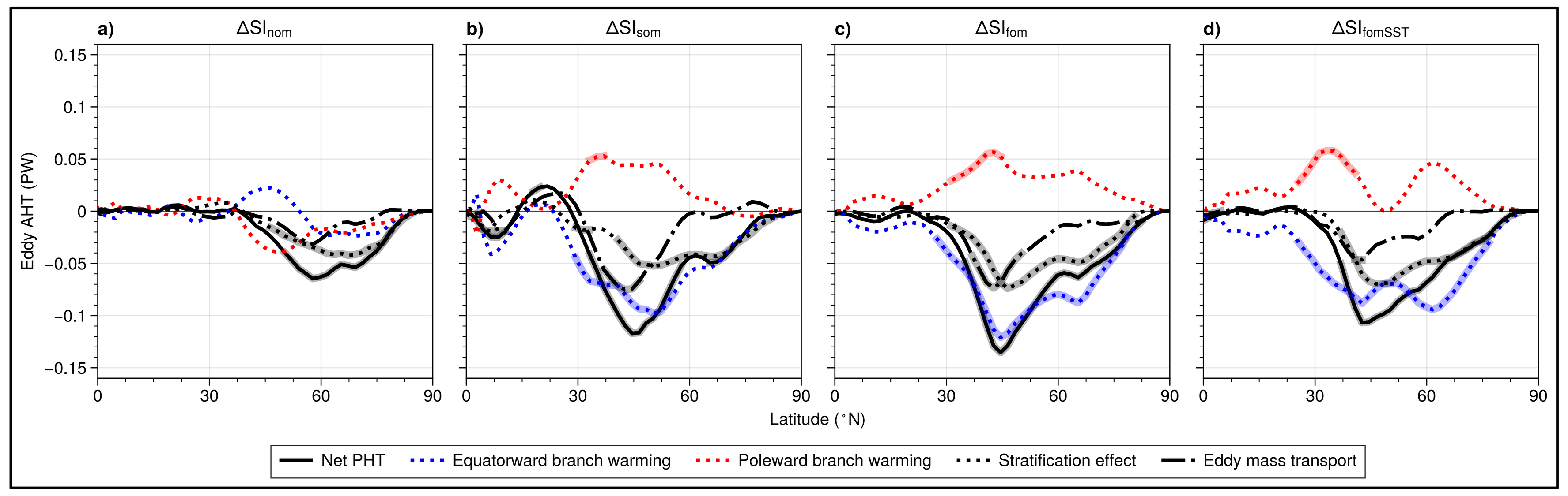

Figure 4. Annual mean eddy moist static energy transport. Net eddy AHT response to Arctic sea ice loss (solid black), effective stratification contribution (dotted black), eddy mass transport contribution (dash-dotted black), contribution from the warming of the poleward branch (dotted red) and contribution from the warming of the equatorward branch (dotted blue). (a) Response in NOM. (b)-(d) As in (a) but for SOM, FOM and FOMSST respectively.

Model hierarchy

Atmosphere-only (NOM) : A prescribed ocean and sea configuration with prescribed sea ice concentration (SIC), sea ice thickness (SIT) and sea surface temperature (SST).
Slab ocean model (SOM): A slab ocean model and sea ice configuration with a SOM substituted for POP2 to remove the effect of interactive ocean dynamics and again, CICE4 for the sea ice component.[4]
Full ocean model (FOM): A dynamical ocean and sea ice configuration with the ocean model POP2 and the sea ice model CICE4.

Key results

- Ocean-atmosphere coupling leads to a stronger a deeper warming in response to Arctic sea ice loss and a full ocean model appears to be required to capture the *full* signal.
- The North Atlantic storm track weakens in response to Arctic sea ice loss, but only significantly when the ocean can interact with the atmosphere. However, prescribing the SST response from the FOM simulations into an atmosphere-only model provides very similar results.
- Over the North Atlantic, thermodynamic coupling modulates the intensity of the eddy heat flux weakening while ocean dynamics control the location of the signal pattern.
- The high latitude AHT weakening is driven by a warming of the equatorward branch of the circulation while the midlatitude reduction arises from a slow down of the eddy mass transport.

Future Directions

In previous work[5], we found a strong opposition in atmosphere-only simulations between the high latitude stratification response to sea ice loss and a dynamical.

Using the same sea ice nudging method, we can isolate the role of greenhouse gas forcing in the absence of sea ice loss. This would allow for testing of the robustness of this opposition while also testing for the additivity of the storm track responses.

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