Sensitivity of the Atlantic meridional overturning circulation (AMOC) to the tropical Indian Ocean warming

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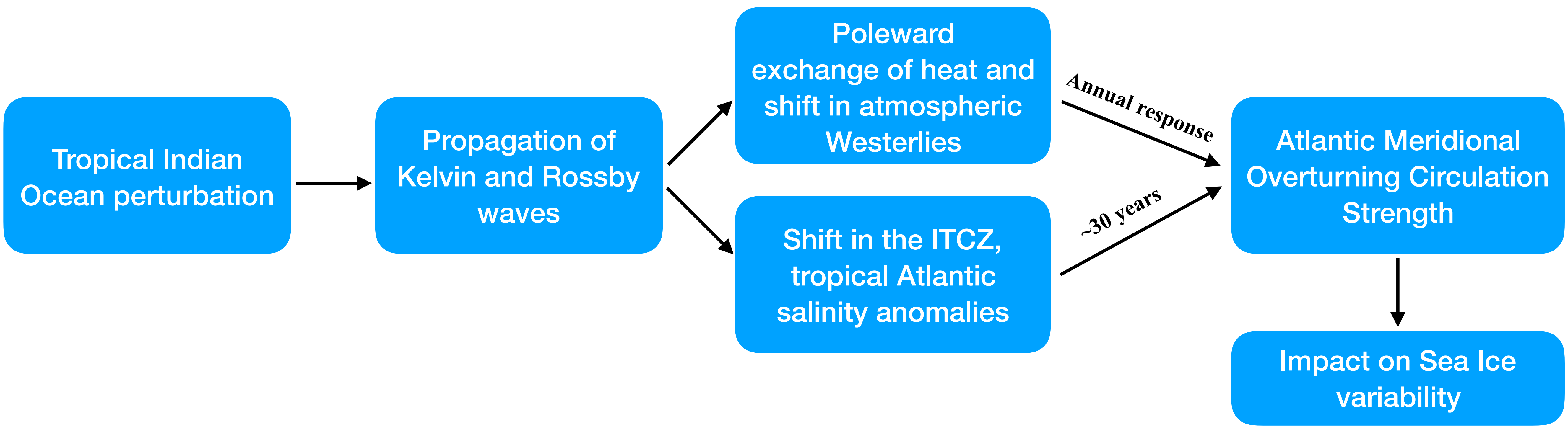

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Abstract

The Arctic and North Atlantic Ocean play a fundamental role in Earth's water cycle, distribution of energy (i.e. heat), and the formation of cold, dense waters. Through the Atlantic meridional overturning circulation (AMOC), heat is transported to the high-latitudes. Classically, the climate impact of AMOC variations has been investigated through hosing experiments, where anomalous freshwater is artificially added or removed from the North Atlantic to modulate deep water formation. However, such a protocol introduces artificial changes in the subpolar area, possibly masking the effect of the AMOC modulation. Here, we develop a protocol where AMOC intensity is modulated remotely through the teleconnection of the tropical Indian Ocean (TIO), so as to investigate more robustly the impact of the AMOC on climate. Warming in the TIO has recently been shown to strengthen the Walker circulation in the Atlantic through the propagation of Kelvin and Rossby waves, increasing and stabilizing the AMOC on longer timescales. Using the latest coupled-model from Insitut Pierre Simon Laplace (IPSL-CM6), we have designed a three-member ensemble experiment nudging the surface temperatures of the TIO by -2°C, +1°C, and +2°C for 100 years. The objectives are to better quantify the timescales of AMOC variability outside the use of hosing experiments and the TIO-AMOC relationship. In each ensemble member, there are two distinct features compared to the control run. The initial changes in AMOC (≤20 years) are largely atmospherically driven, while on longer timescales is largely driven by the TIO teleconnection to the tropical Atlantic. In the northern North Atlantic, changes in sensible heat fluxes range from 15 to 20 W m^{-2} in all three members compared to the control run, larger than the natural variability. On the longer timescales, AMOC variability is strongly influenced from anomalies in the tropical Atlantic Ocean. The TIO teleconnection supports decreased precipitation in the tropical Atlantic Ocean during warming (opposite during TIO cooling) events, as well as positive salinity anomalies and negative temperature anomalies. Using lagged correlations, there are the strongest correlations on scales within one year and a delayed response of 30 years. In comparing the last 20 years, nudging the TIO induces a 3.3 Sv response per 1°C change. In summary, we have designed an experiment to investigate the AMOC variability without directly changing the North Atlantic through hosing, making way for a more unbiased approach to analysing the AMOC variability in climate models.

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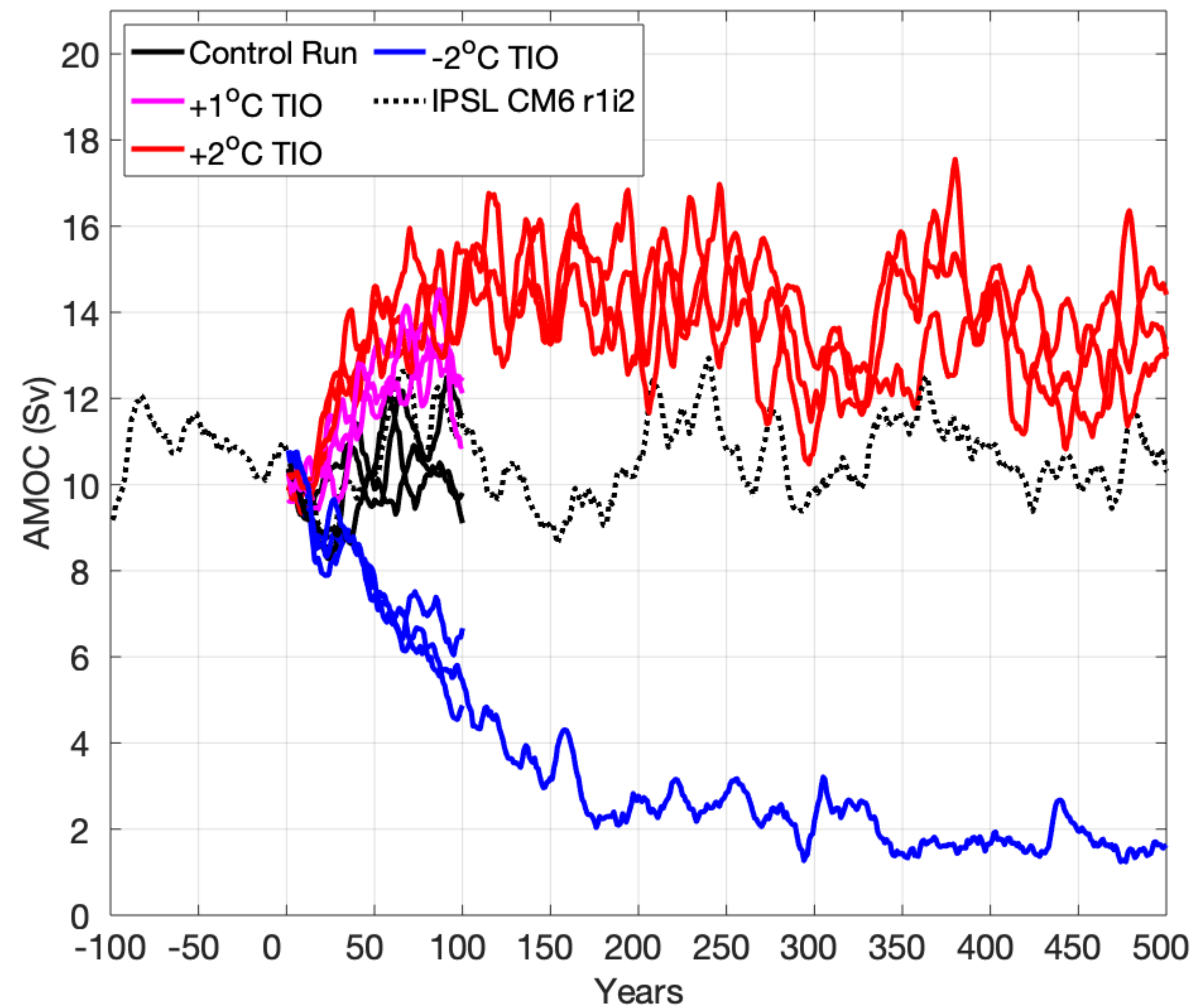
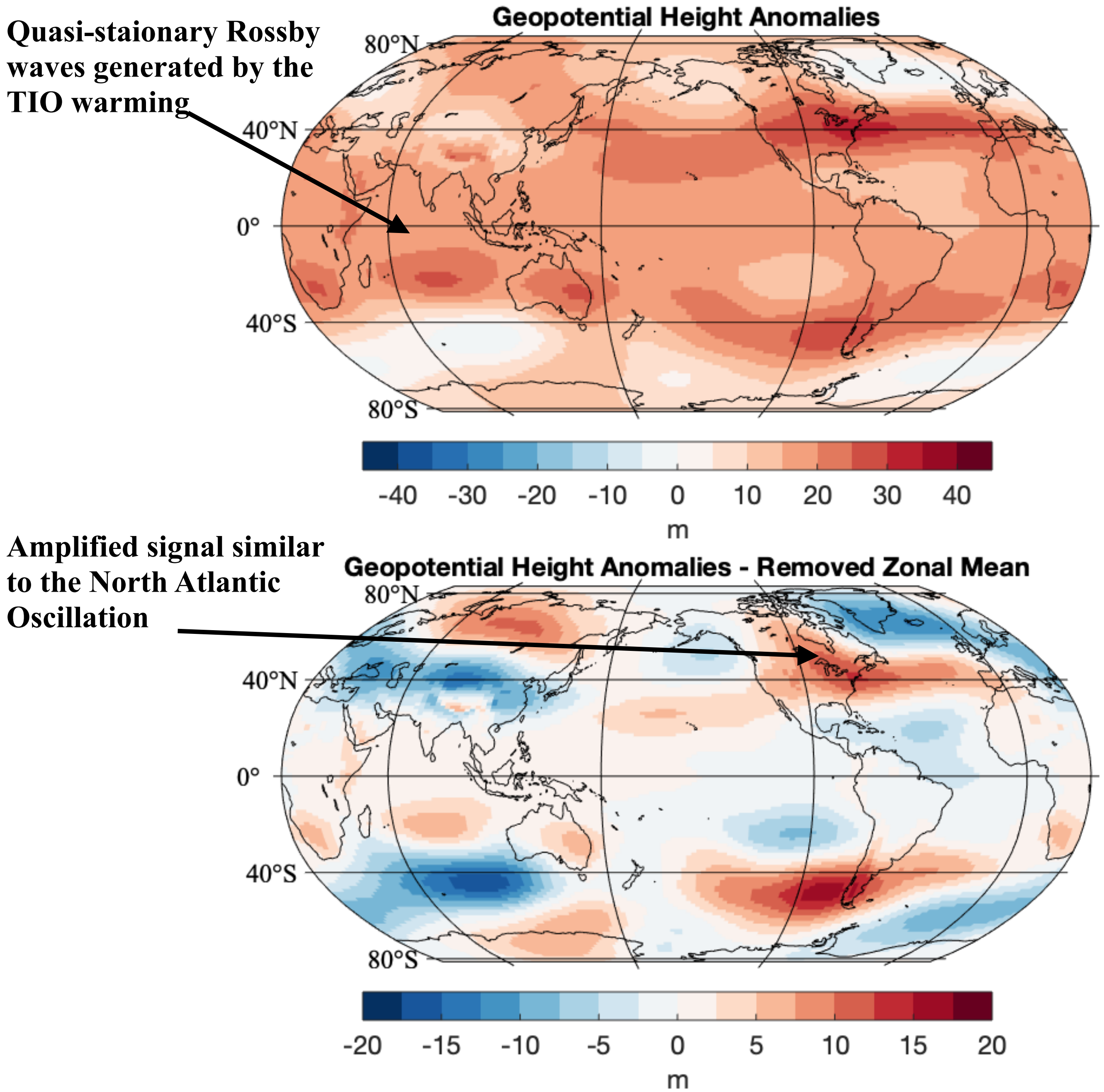
Tropical Indian Ocean perturbation

- The tropical Indian Ocean (TIO)
  - **Restoring = 40 W m^{-2} K^{-1}** within the surface mixed layer
  - Nudging to 30°-100°E, 30°S-30°N in the **IPSL CM6 piControl r1i2**
- Three members of **Control Run**, **+1°C**, **+2°C**, **-2°C**
  - Sea surface temperature changes of 0.7°C, 1.4°C, and -1.4°C respectively
  - Extended **+2°C** and **-2°C** members for further analyses
- Experiment setup based on the findings of Hu and Fedorov, 2019



AMOC changes in response to changes in the TIO sea surface temperature. An 11-year moving-mean is applied to all the members. AMOC is defined as the maximum overturning streamfunction at 48°N below depths of 500m. In analysing the response to the TIO, the transient period is considered as the initial 100-years of each member.

Propagation of Kelvin and Rossby waves



- Atmospheric teleconnections to the Atlantic basin and Arctic during a relatively warm tropical Indian Ocean (TIO)
  - Propagation of Rossby and Kelvin waves
  - Poleward transports of heat and moisture
  - Increased subpolar Westerlies
  - Northward ITCZ and positive salinity anomalies in the tropical Atlantic

Anomalies in geopotential height (A) at the 506 hPa level in the IPSL CM6 vertical coordinate, close to 500 hPa, for the +2°C warming members. (B) Similar to (A) but with the zonal mean removed. Anomalies shown are from years 1-30.

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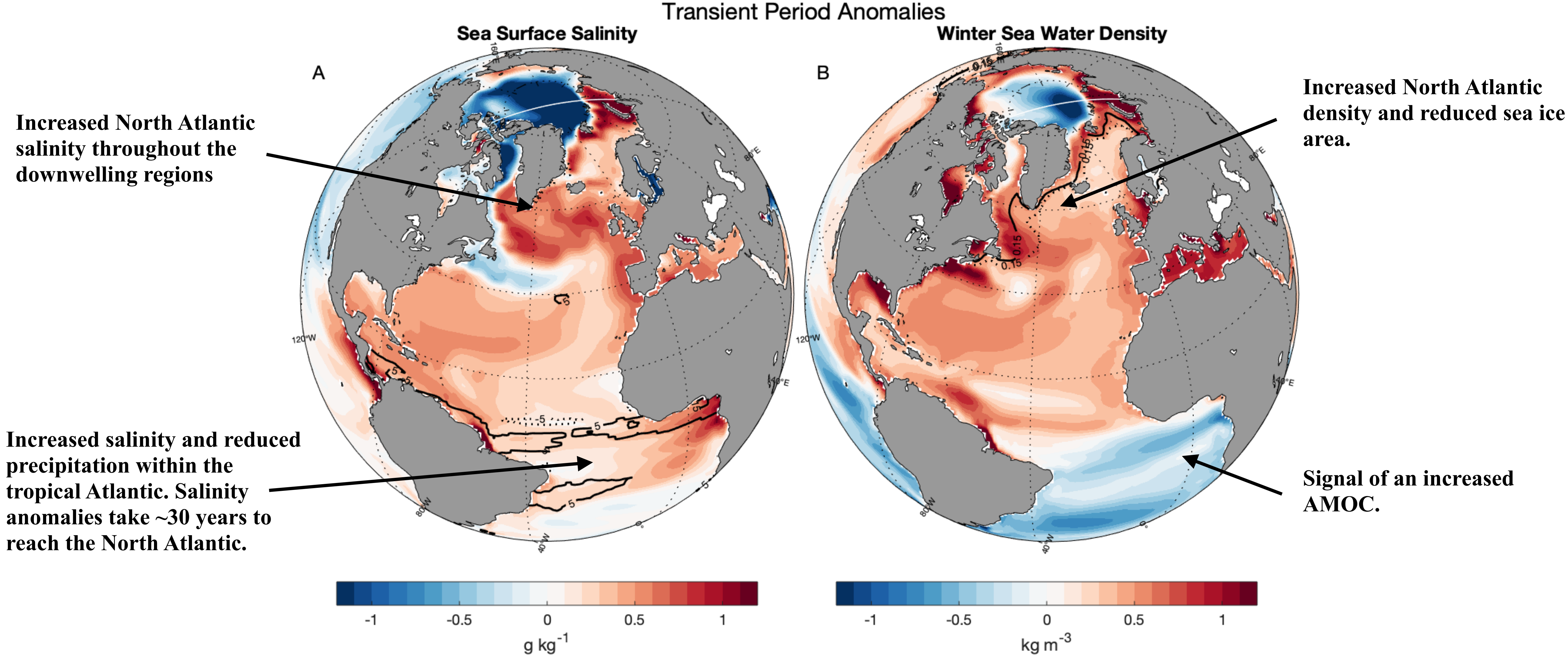
Shift in the ITCZ, tropical Atlantic salinity anomalies



Annual mean sea surface salinity and evaporation minus precipitation (contours) anomalies (A). Winter mean surface density anomalies and sea ice extent. (B) The solid contour represents the +2°C ensemble mean (0.15 concentration) and the dashed contour is the control run mean. The anomalies are from the +2°C ensemble members relative to the control run mean. Similar results occur within the +1°C ensemble members and the opposite holds true in the -2°C ensemble members. Anomalies shown are from years 11-100.

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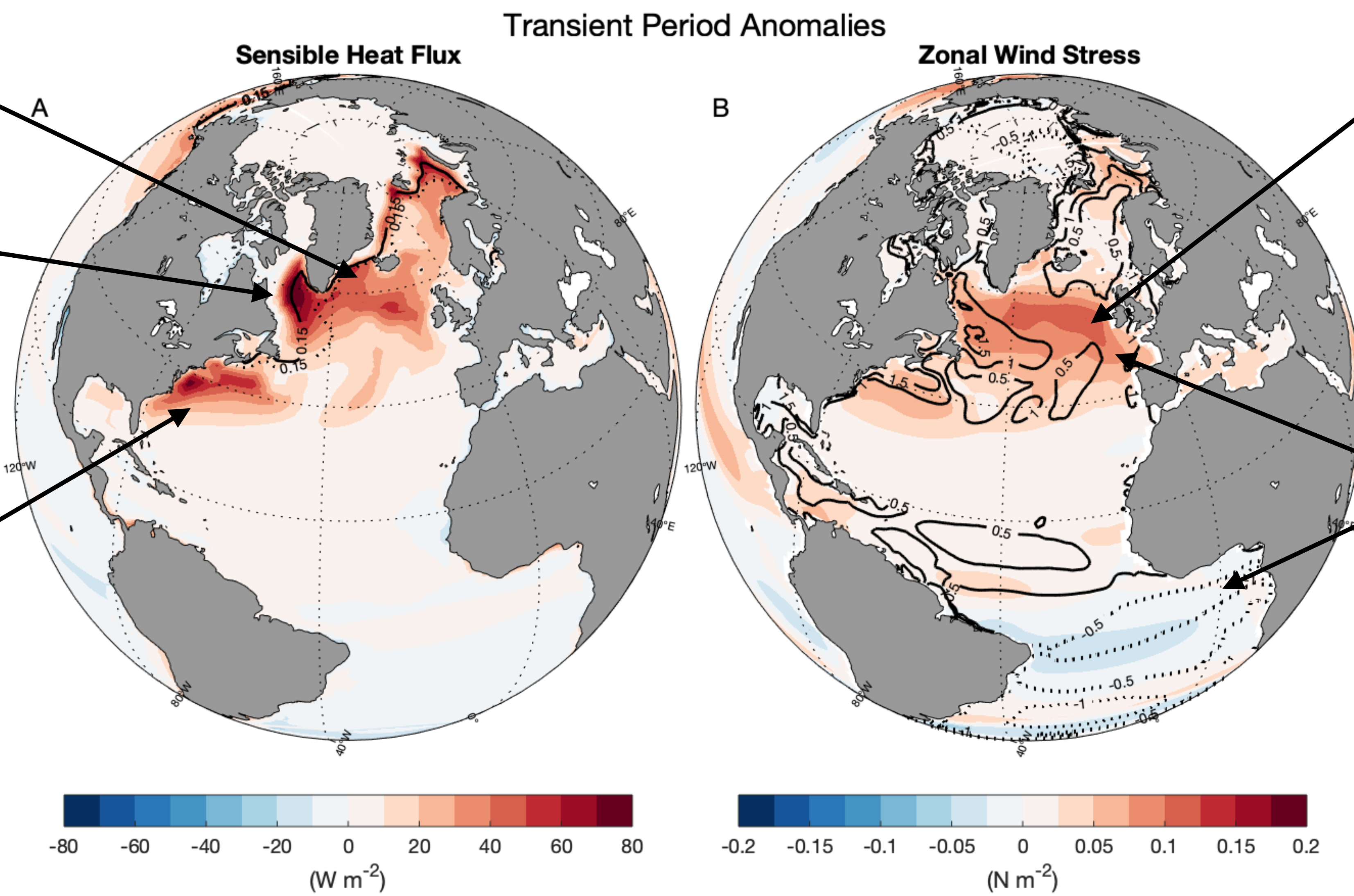
Poleward exchange of heat and shift in atmospheric Westerlies

Increased sensible heat in downwelling regions

Reduced winter sea ice extent and increased sensible heat fluxes within the Labrador Sea region

Northward shift in the Gulf Stream seen in sensible heat flux, zonal wind stress, and density.



Increased zonal wind stress and North Atlantic Ekman driven transports

Increased North Atlantic surface density and a surface signal of AMOC response.

Mean winter sensible heat flux anomalies from the +2°C ensemble members; the solid contour represents the sea ice extent (0.15 concentration) and the dashed contour is the control run mean (A). Winter mean zonal wind stress and surface density (in contours) anomalies (B). The anomalies are estimated from the +2°C ensemble members relative to the control run mean. Similar results occur within the +1°C ensemble members and the opposite holds true in the -2°C ensemble members. Anomalies shown are from years 11-100.

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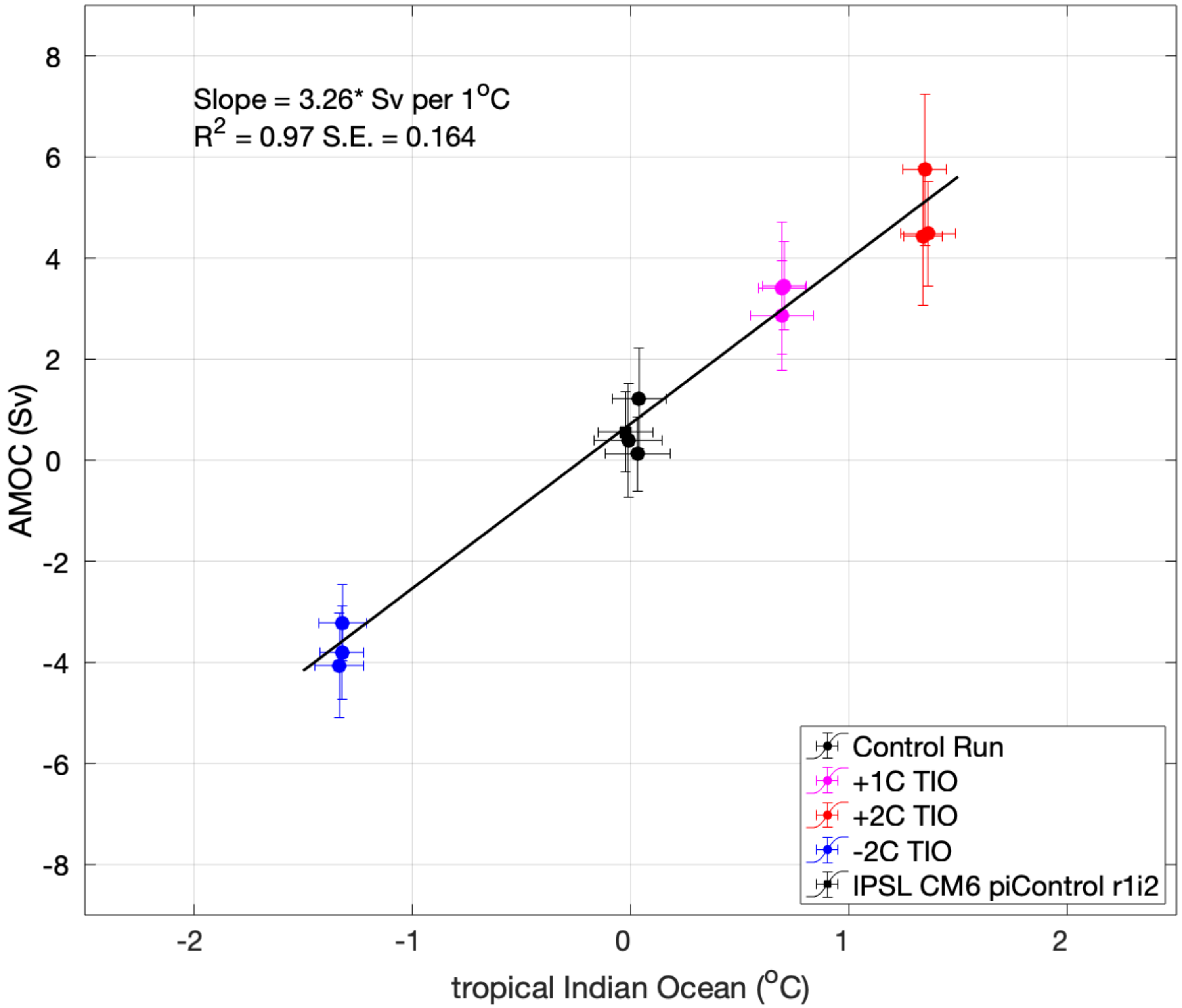
Atlantic Meridional Overturning Circulation Strength



Linear regression between the tropical Indian Ocean (TIO) sea surface temperature and the maximum AMOC at 48°N for the years 81-100 of each ensemble member. AMOC and TIO sea surface temperature are relative to the mean control run.

Key Results

- The tropical Indian Ocean (**TIO**) sea surface temperature can be used to **remotely manipulate AMOC**
- **Robust, linear pattern** of the AMOC-TIO relationship resulting in the IPSL CM6
  - Similar results with the NCAR CESM in Hu and Fedorov (2019)
  - Annual changes driven through teleconnections in the **zonal wind stress** (Ekman transports), **sea ice**, and **sensible heat fluxes**
  - **Salinity anomalies in the tropical Atlantic** are transported northward (~30 year lag)

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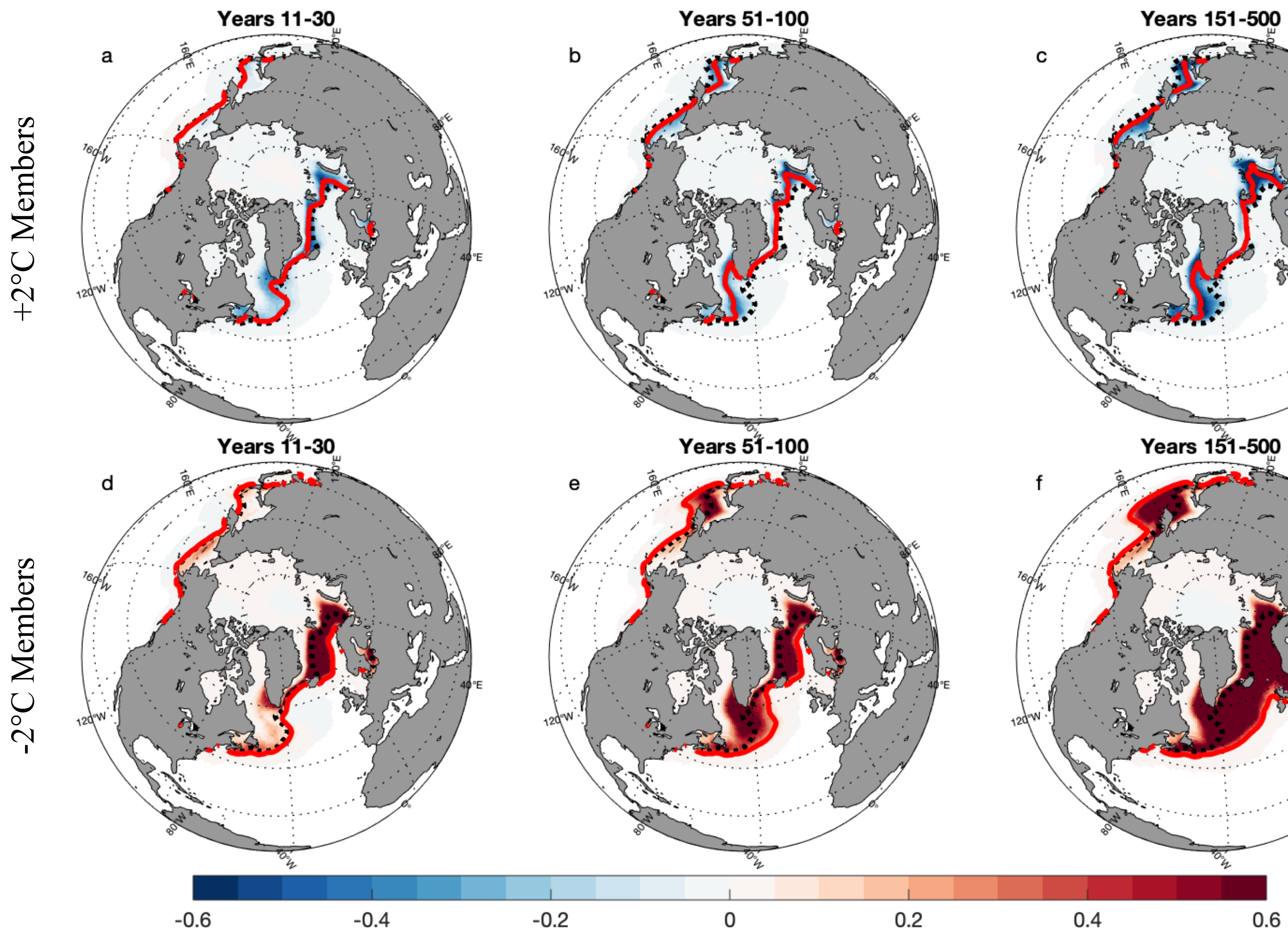
Impact on Sea Ice Variability



<u>Additional Results</u>

- New approach to study the impacts of AMOC on the Arctic sea ice
    - Hosing experiments can introduce bias
- The tropical Indian Ocean teleconnection can be used to investigate AMOC relationships during increased/decreased Arctic sea ice extent

Mean winter sea ice concentration anomalies in +2°C (a-c) and -2°C (d-f) members relative to the Control Run. The red contour is the mean +2°C and -2°C, respectively, 0.15 concentration and the black contour is the 0.15 concentration in the Control.