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Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation

Florian Sévellec^{1*}, Alexey V. Fedorov² and Wei Liu²

¹Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, UK. ²Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06511, USA. *e-mail: f.sevellec@soton.ac.uk

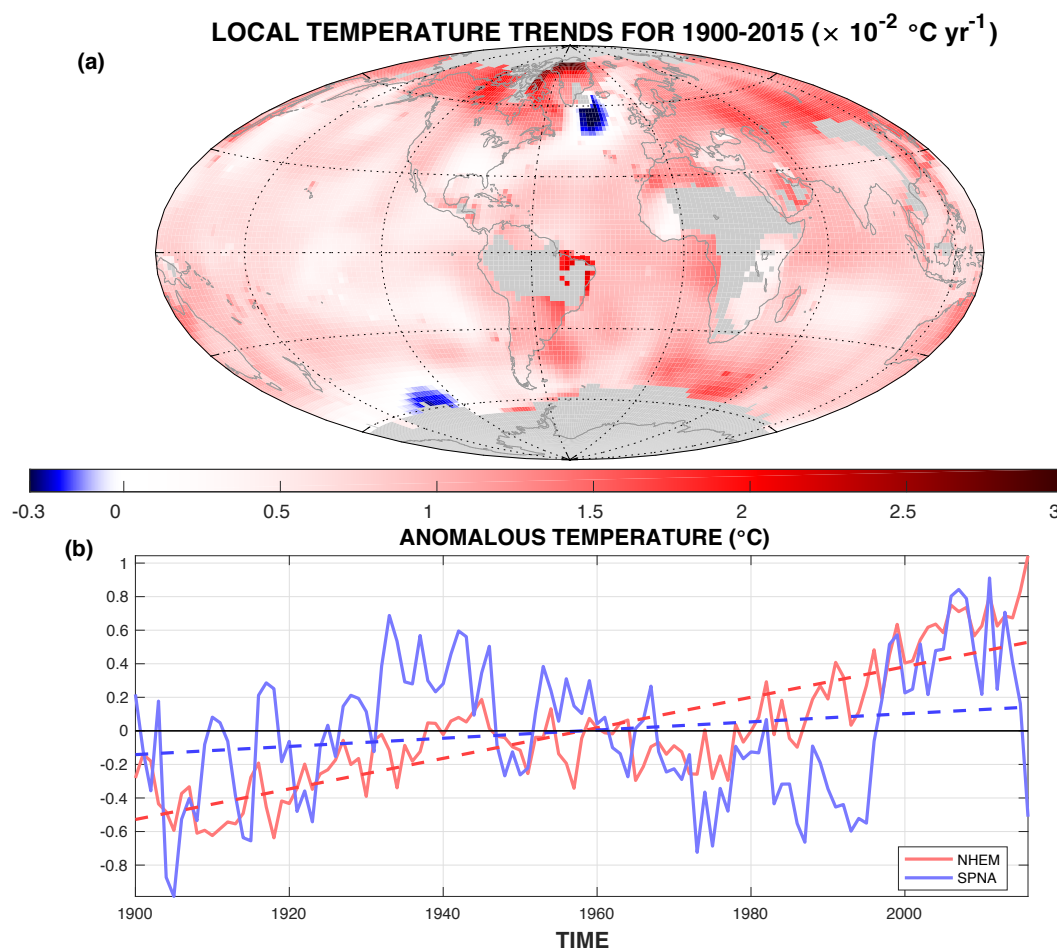


FIGURE S1: Temperature changes over the past century. (a) A global map of local surface air temperature trends between 1900 and 2015. The subpolar North Atlantic shows a generally weaker warming with a localized region of negative trend south of Greenland often referred to as the Warming Hole and conjectured to be caused by the AMOC slow-down^{3,4}. NASA GISS temperature were used; gray indicates insufficient data. (b) Spatially-averaged temperature anomalies in the Northern Hemisphere (NHEM, red solid line) and the subpolar North Atlantic (SPNA, blue solid line) for the same period. Dashed lines indicate the corresponding linear trends. Here, the subpolar North Atlantic is defined as a rectangular region confined to 50°W - 10°W and 50°N - 60°N. The warming trend is significantly weaker in the subpolar North Atlantic than that for the entire Northern Hemisphere, which suggests an AMOC slow-down.

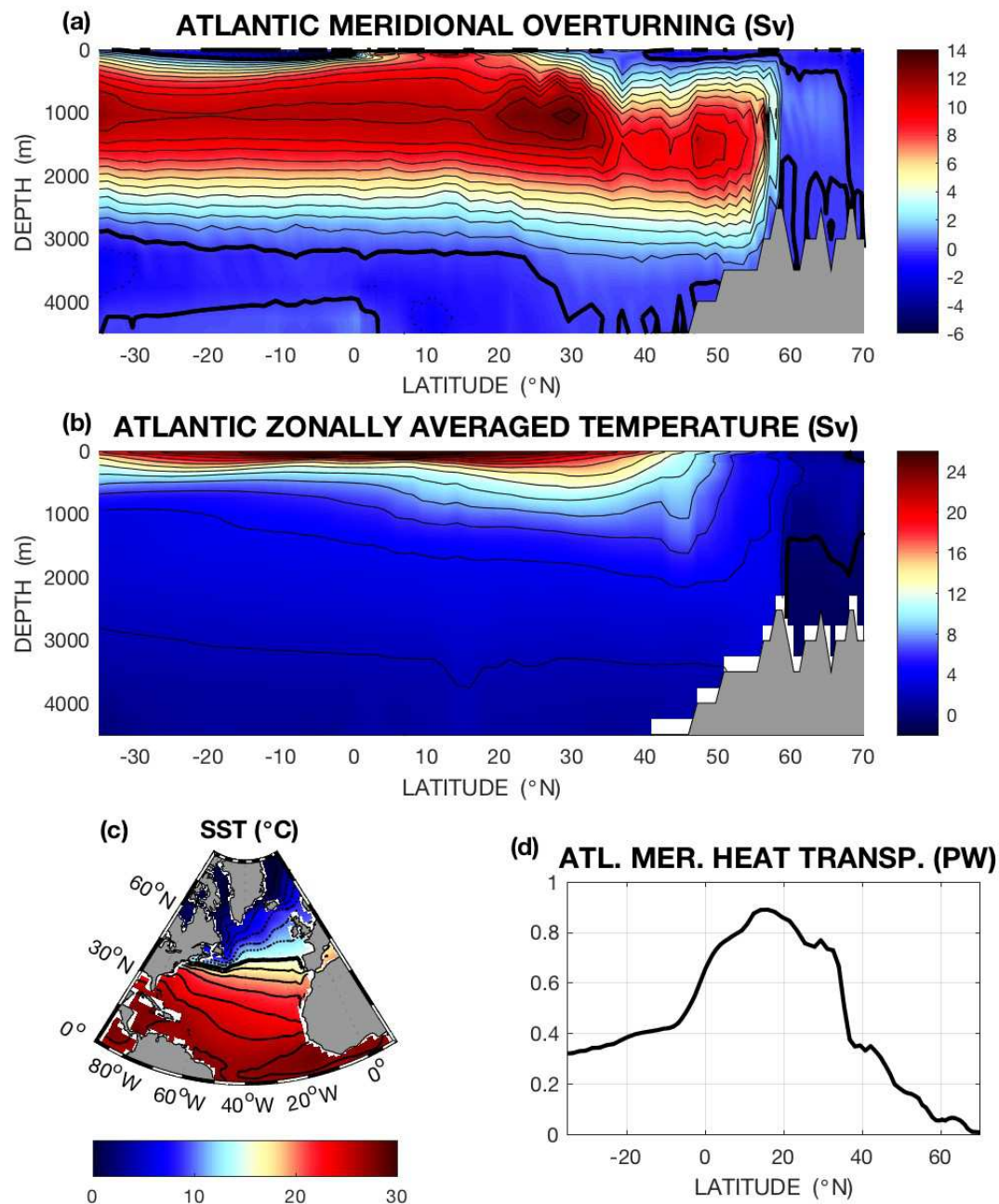


FIGURE S2: The climatological mean state of the Atlantic ocean as reproduced by the full ocean GCM. (a) Zonally averaged streamfunction showing the AMOC; contour intervals (CI) are 1 Sv; the thick solid line corresponds to 0°C, plain and dotted lines indicate higher and lower values, respectively. (b) Zonally averaged temperature; CI are 2°C, the thick solid line corresponds to 0°C, plain lines indicate higher values. (c) SST; CI are 2°C, the thick solid line corresponds to 15°C, plain and dotted lines indicate higher and lower values, respectively. (d) Meridional heat transport as a function of latitude. The figure is modified from Sévellec and Fedorov (2015)²³.

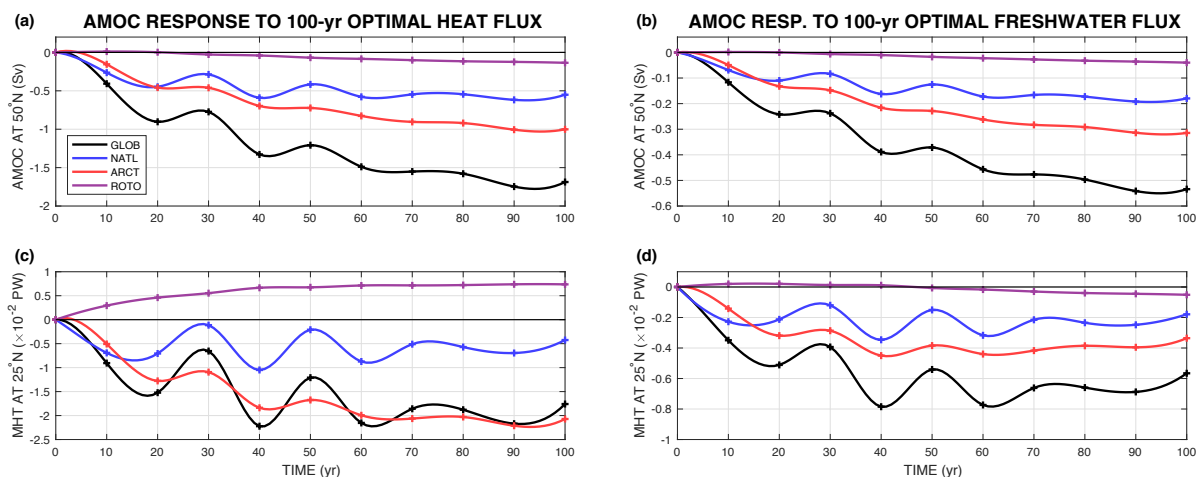


FIGURE S3: The AMOC response to the 100-yr optimal (left) heat and (right) freshwater fluxes. The plot describes changes in the Atlantic ocean (a,b) meridional volume transport at 50°N and 1,500 m depth and (c,d) heat transport (MHT) at 25°N computed by the forward GCM after the optimal fluxes were imposed. The model results are shown as small crosses connected with a cubic spline interpolation. The corresponding patterns of the optimal fluxes were displayed in Fig. 3d and h. The AMOC decrease after 100 yr is equal to the optimal impact of 100-yr heat and freshwater fluxes shown in Fig. 4a and b. The AMOC total response to the imposed fluxes (GLOB, black line) is again split into separate responses to fluxes applied over different geographical regions: the Arctic (ARCT, red line), the North Atlantic (NATL, blue line), and the rest of the ocean (ROTO, purple line). Note that the impacts of heat fluxes are several times greater.

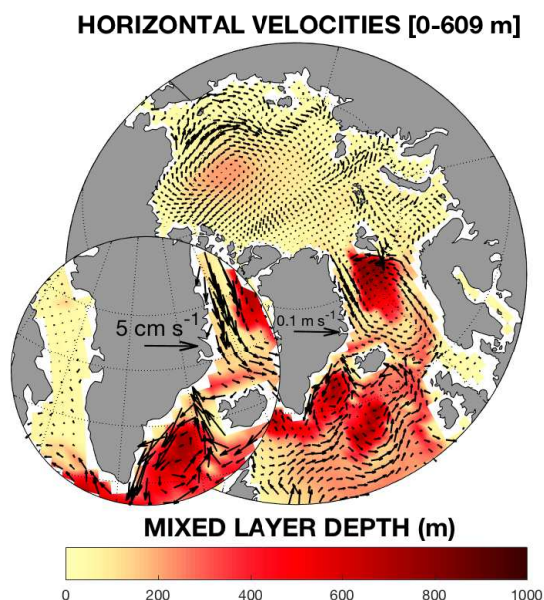


FIGURE S4: Ocean horizontal velocities and mixed layer depth for the climatological mean state of the full ocean GCM. A vertical average (from 0 to 609 m) of the annual-mean horizontal velocity (arrows) and the depth of model ocean mixed layer (colors) are shown. Heat and freshwater anomalies are exported from the Arctic to the North Atlantic by the East Greenland current and the Greenland-Iceland ridge overflow, generating a net southward flow in the upper ocean.

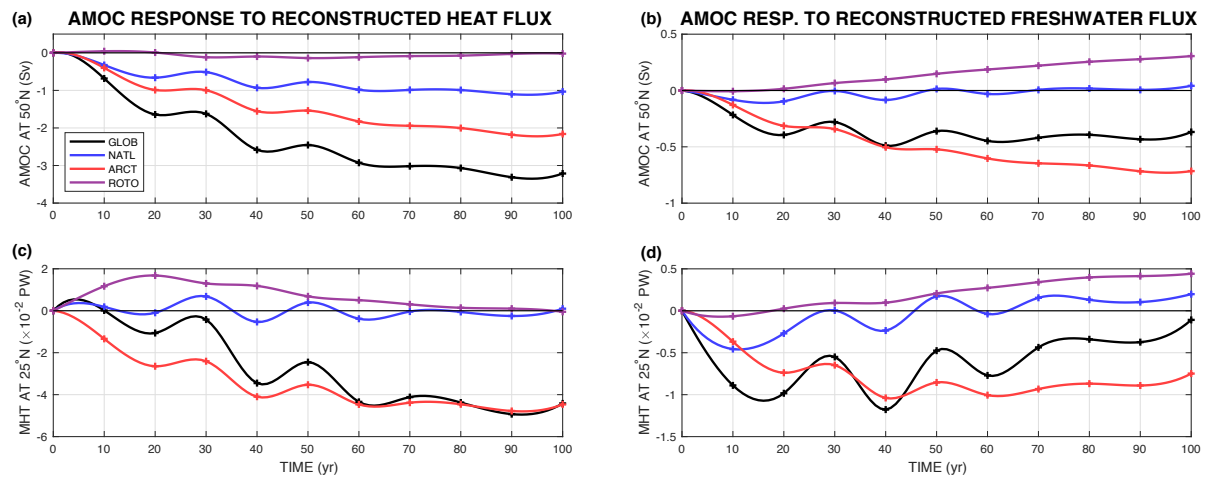


FIGURE S5: The model AMOC response to the observed flux anomalies. As in Fig. S3, but when we impose the reconstructed anomalies in (left) heat and (right) freshwater fluxes shown in Fig. 5a,b. The AMOC response to the combined anomalies was shown in Fig. 5c,d.

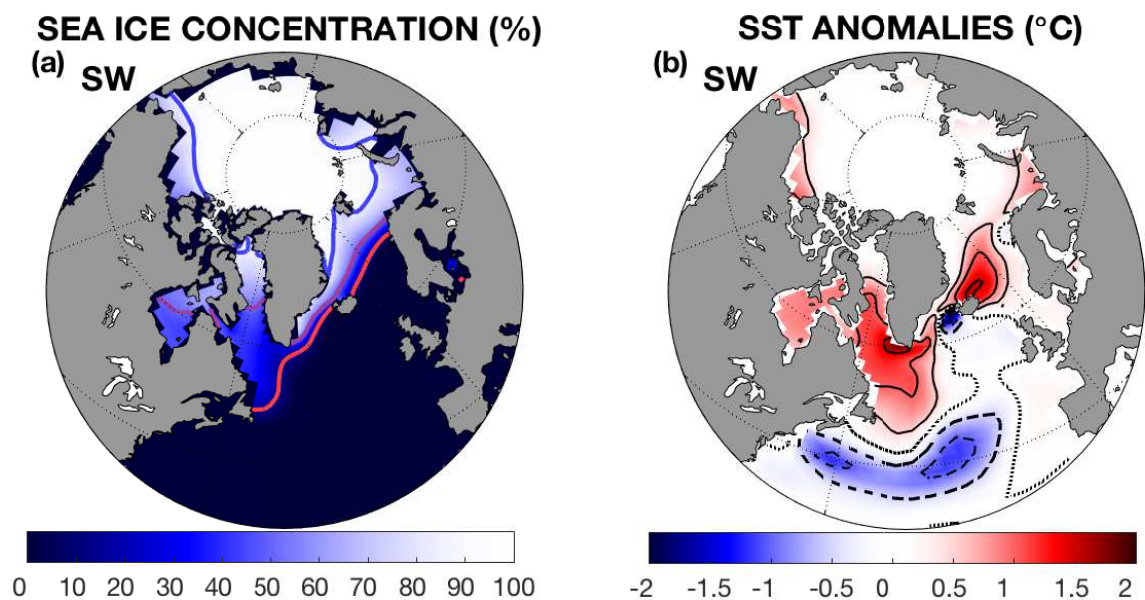


FIGURE S6: Arctic sea ice retreat and SST anomalies simulated by the climate GCM. As in Fig. 6b,d but for the SW experiment.

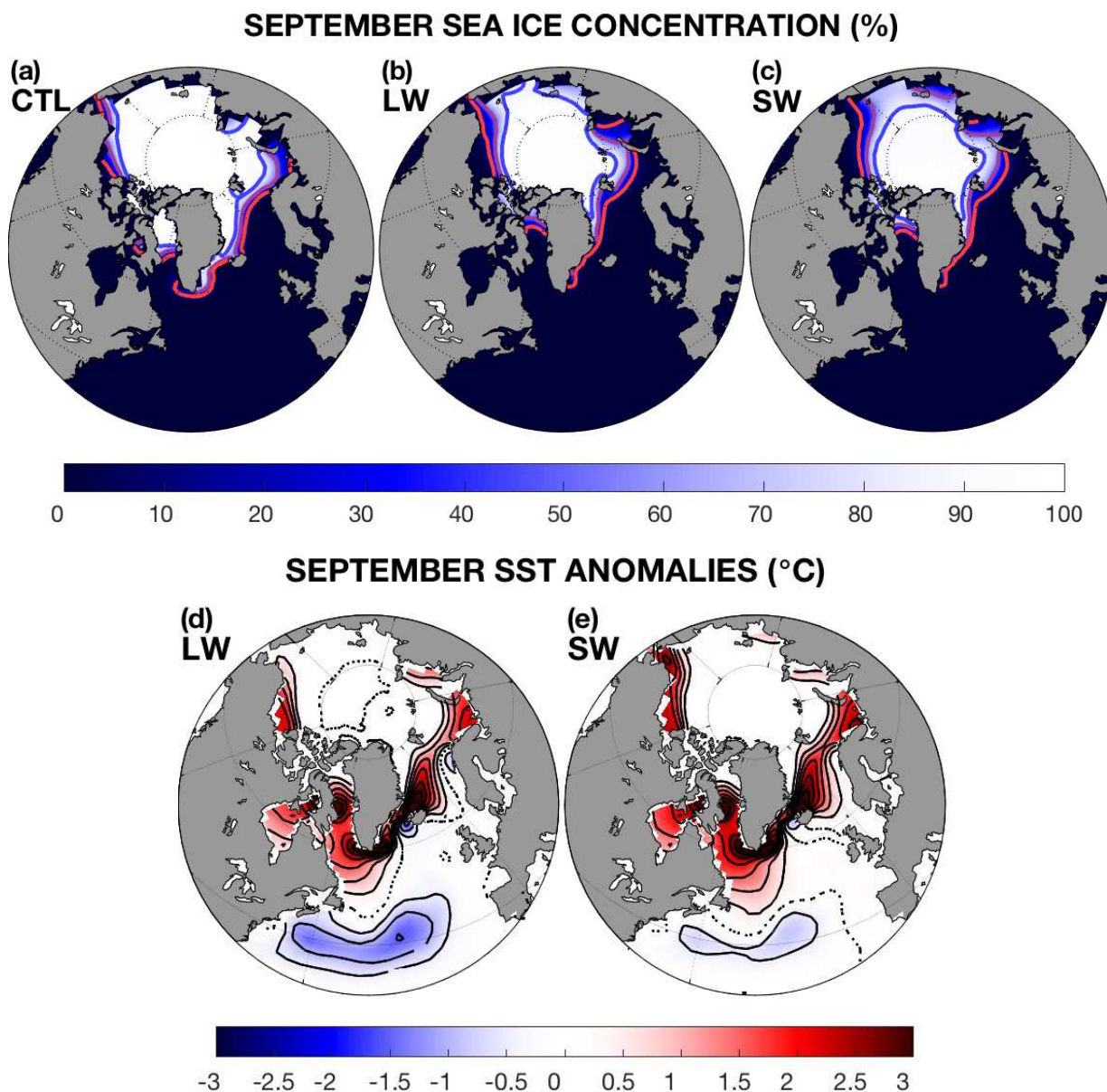


FIGURE S7: Arctic sea ice retreat and SST anomalies simulated by the climate GCM during September. (a-c) September mean sea ice concentration for the CTL, LW and SW experiments. The blue, purple and red contours mark 85%, 50%, and 15% sea ice concentrations. (d,e) September SST anomalies (in °C) for the LW and SW experiments with respect to the control SST contour intervals are 0.5°C. Model output was averaged within the last 50 years of the CTL run, and within years 151-200 for the perturbation experiments (see Fig. S8).

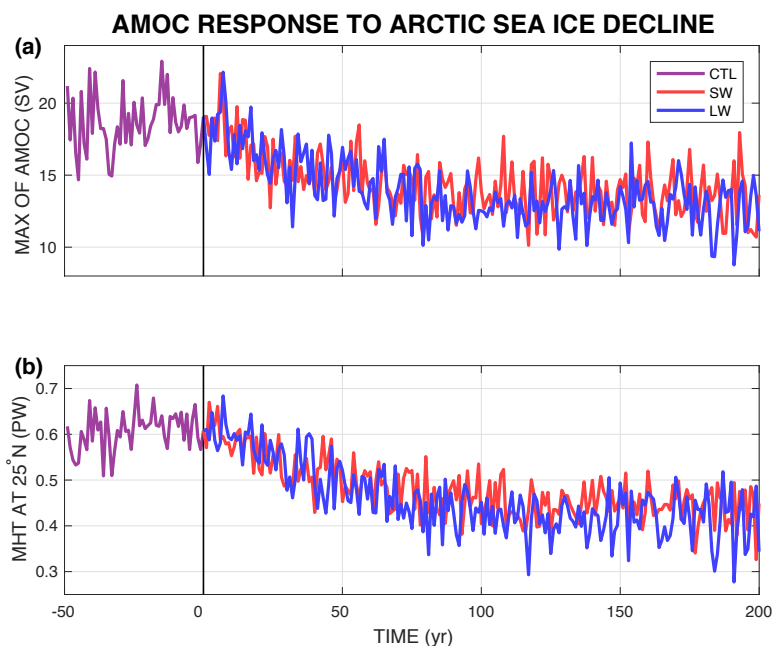


FIGURE S8: The impacts of Arctic sea ice retreat on the AMOC in the LW and SW coupled model experiments. (a) AMOC maximum volume transport (estimated between 10°N and 70°N and between 500 m and 5000 m) and (b) oceanic meridional heat transport (MHT) at 25°N. Both perturbations experiments start from the CTL run; modifications to sea ice radiative balance are imposed at time zero and maintained for the duration of each experiment.