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Persistent ocean anomalies as a response to Northern Hemisphere heating induced by biomass burning variability

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This supplemental material includes 8 supplementary figures (S1-S8).

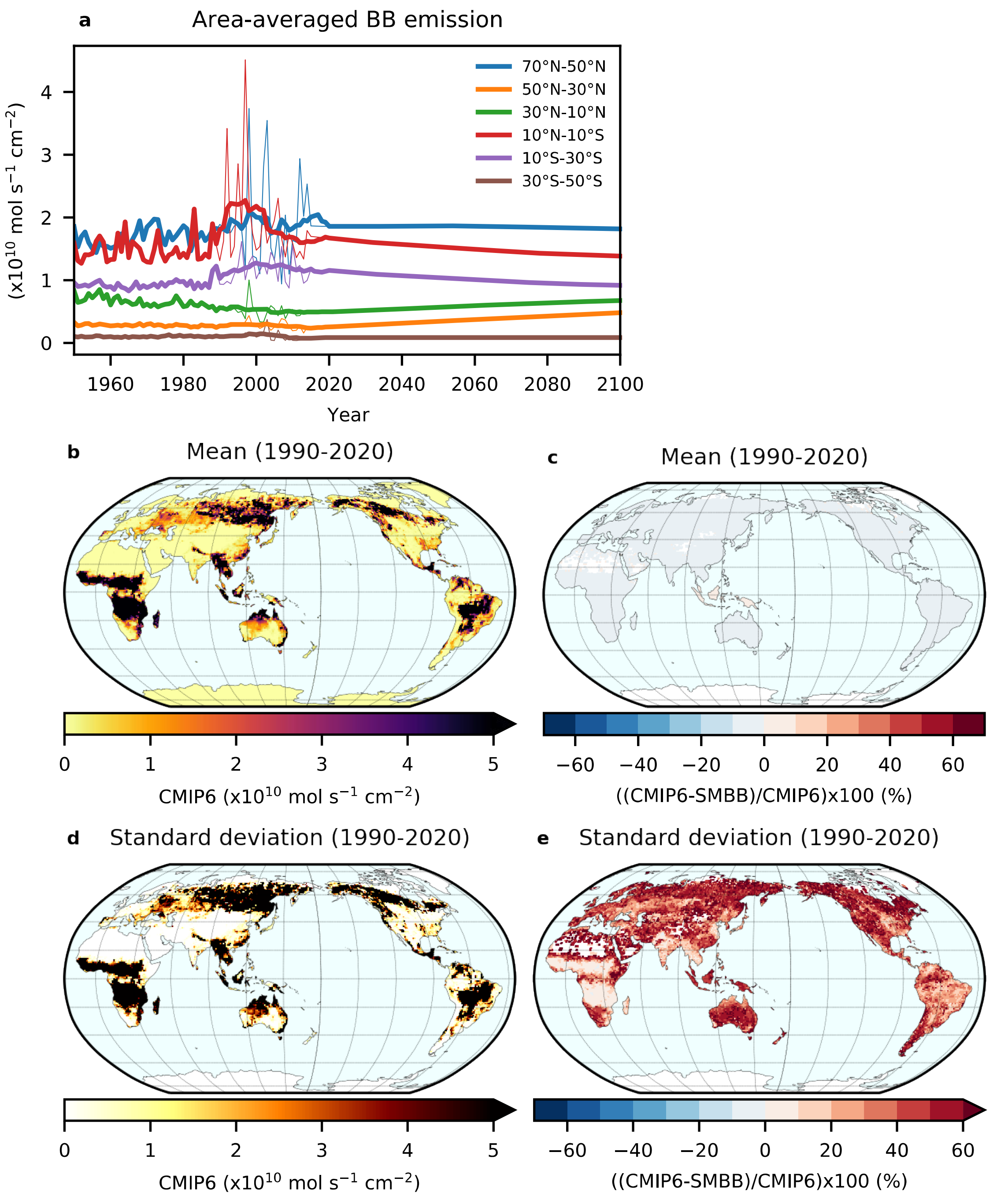

Fig. S1. Differences in model forcing fields for biomass burning (BB) aerosol emissions between the CMIP6 and SMBB simulations. (a) CMIP6 (thin lines) and SMBB (thick lines) area-averaged time series of BB aerosol emissions. The grey-shaded period corresponds to when an 11-year running mean was applied to the standard BB4CMIP6 to generate BB aerosol forcings for SMBB simulations. (b–d) 1990–2020 mean and standard deviation of the BB4CMIP6 and their relative differences from those in the SMBB. The variability of the BB aerosol emission is remarkably reduced in SMBB, especially in the Northern Hemisphere high latitudes and the equatorial regions, while the total emissions are nearly conserved over this period (negligible changes in the mean).

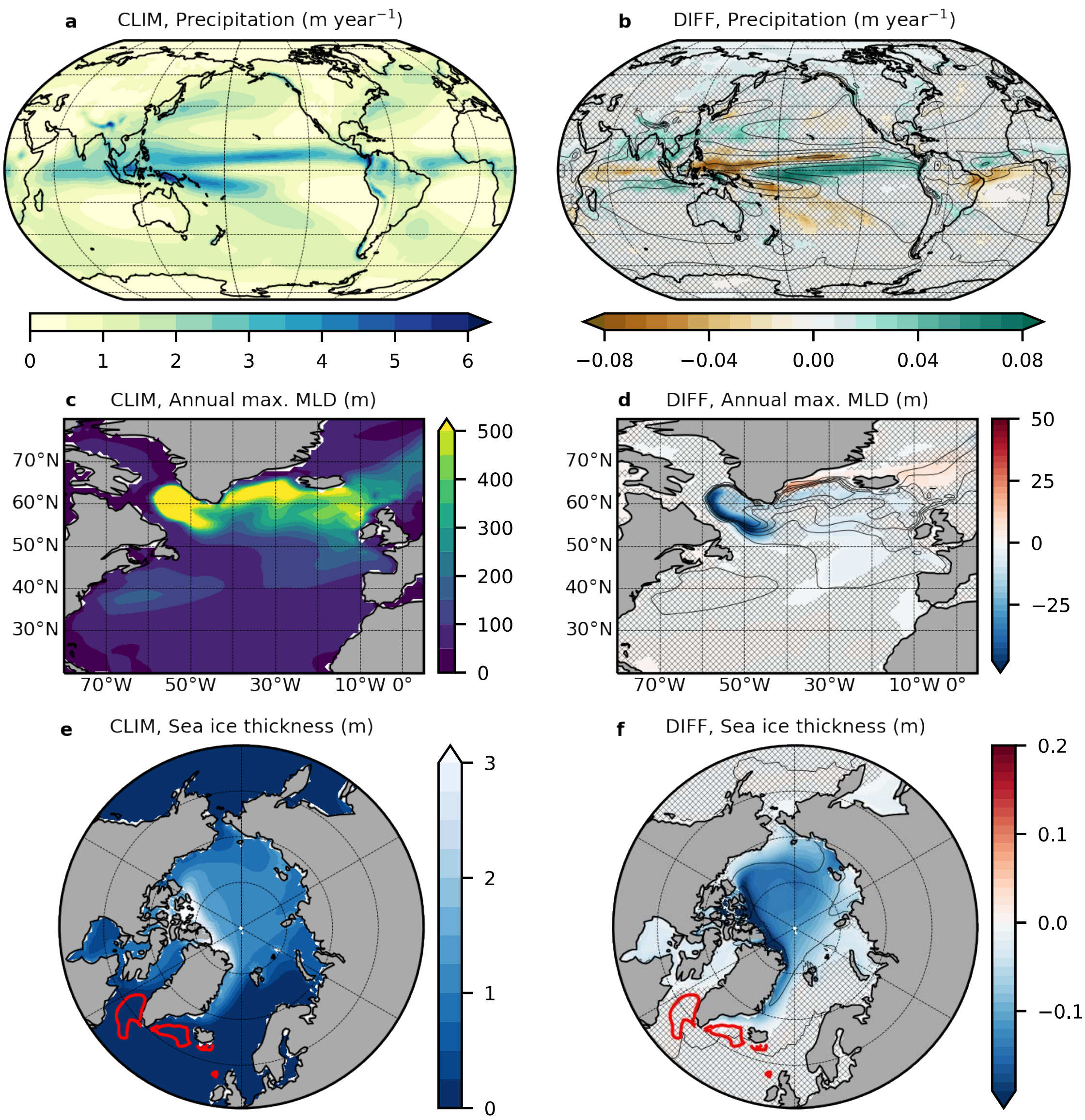

Fig. S2. 100-member ensemble mean climatologies (CLIM, 2000–2020) and differences in CMIP6 and SMBB subensemble means (DIFF, 2000–2020) of (a and b) precipitation (c and d) annual maximum of mixed layer depth (MLD), and (e and f) Arctic sea ice thickness. The northward shifts of the intertropical convergence zone (ITCZ) are identified in the Atlantic and Indian Ocean sectors, but are not apparent in the Pacific region as weak El Niño-like changes co-exist. Contours in (b), (d), and (f) are for the corresponding climatology (same as (a), (c), and (e), respectively). Ocean regions surrounded by red lines in (e) and (f) indicate regions where the annual maximum MLD exceeds 500 m in the 100-member ensemble mean. Statistically insignificant signals at the 95% confidence level are cross-hatched.

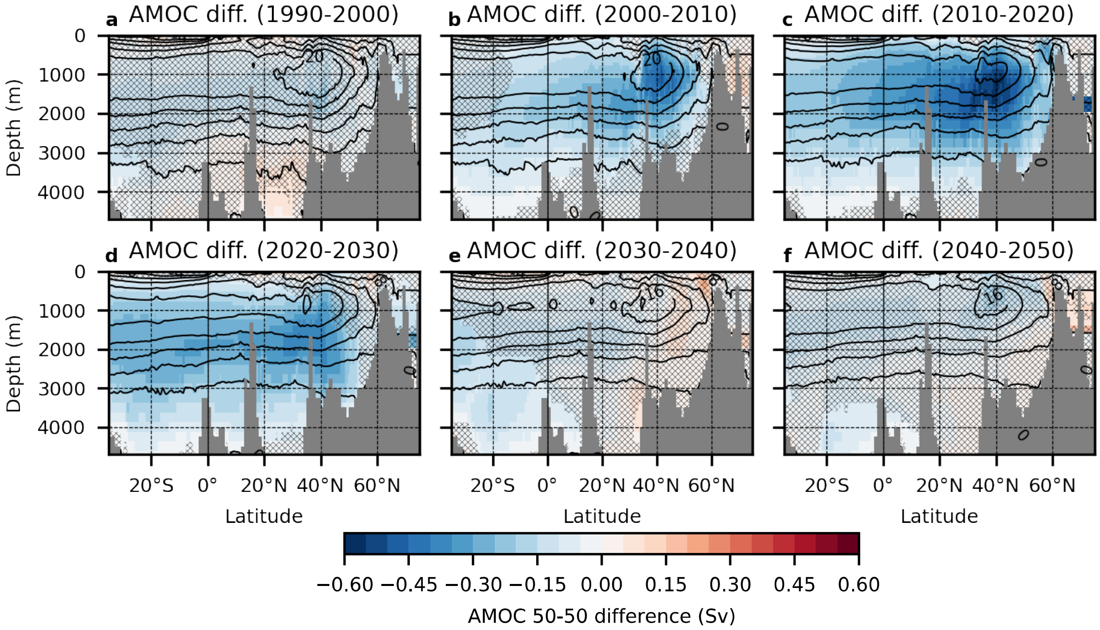

Fig. S3. Difference in CMIP6 and SMBB subensemble means of the Atlantic Meridional Overturning Circulation (AMOC, positive clockwise) over different decades. Climatological mean AMOC (Sv) values for the 100-member ensemble mean over each period are superposed as contours. Statistically insignificant signals at the 95% confidence level are cross-hatched.

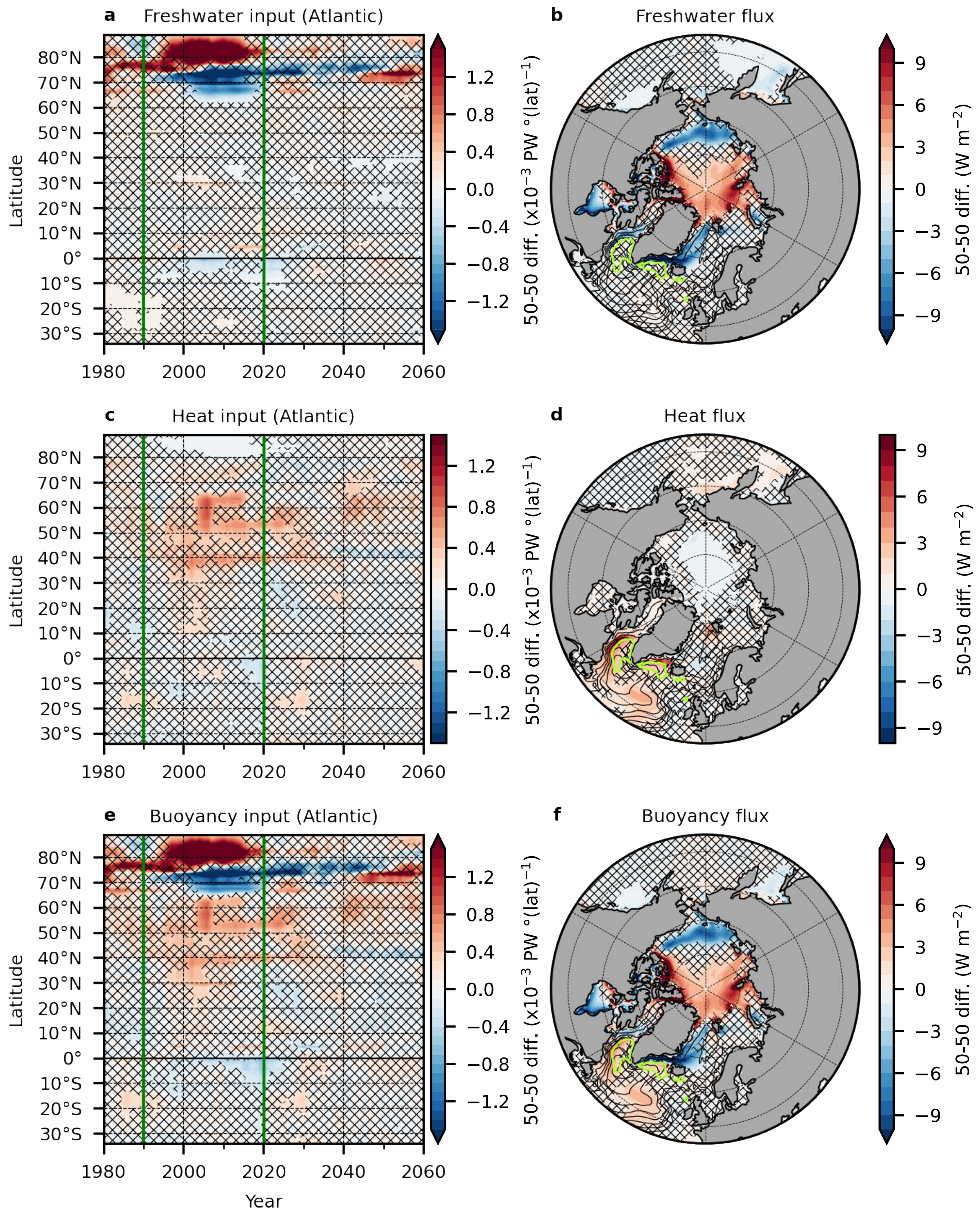

Fig. S4. Differences in CMIP6 and SMBB subensemble means of (a and b) surface freshwater fluxes, (c and d) surface heat fluxes, and (e and f) surface buoyancy fluxes for the Atlantic zonal mean (a, c, and d) and for the Arctic region (b, d, and f) over 2000–2020). Positive differences indicate anomalous ocean freshwater/heat/buoyancy gain in CMIP6 members. Units for freshwater and buoyancy fluxes have been converted to consistent units for comparison by using thermal expansion and haline contraction coefficients estimated from the local sea surface temperature and salinity. An 11-year running mean is applied for (a, c and e). Ocean regions surrounded by green lines in (b, d and f) indicate regions where the winter deep convection exceeds 500 m as the annual maximum in the 100-member ensemble mean. Statistically insignificant signals at the 95% confidence level are cross-hatched.

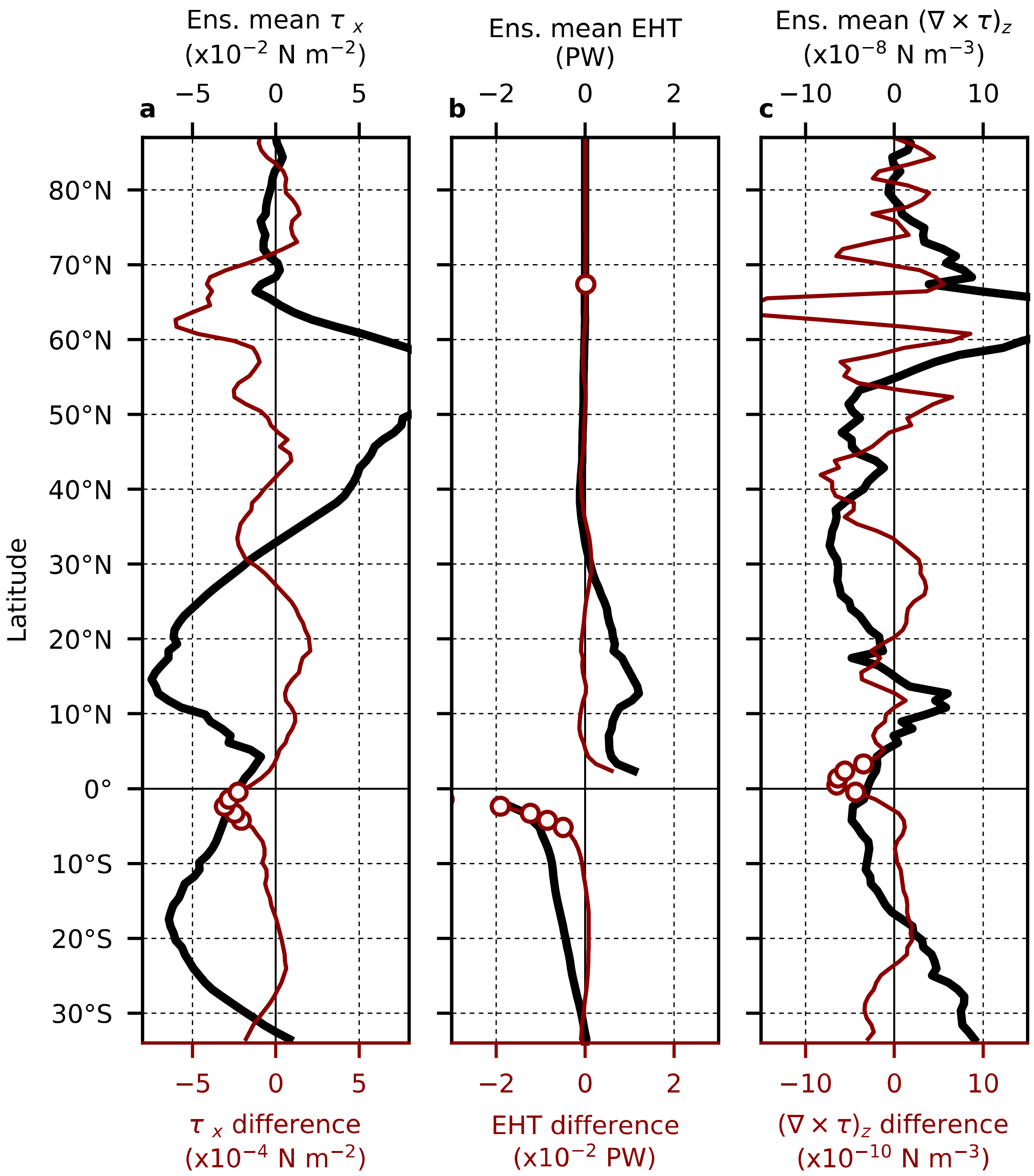

Fig. S5. Atlantic 100-member ensemble mean climatology (black lines with upper x-axis) and subensemble mean differences (CMIP6 minus SMBB, red lines with bottom x-axis) in (a) zonal-mean zonal wind stresses (τ_x, positive eastward), (b) zonally integrated Ekman heat transport (EHT, positive northward), and (c) zonal-mean surface wind stress curl ($(\nabla \times \tau)_z$) over years 2000–2020. Blue-shaded latitudes represent the subtropics in each hemisphere defined from the climatology of zonal-mean surface wind stress curl. The white dots on the differences (red lines) indicate statistically significant differences at the 95% confidence level based on the bootstrapping method.

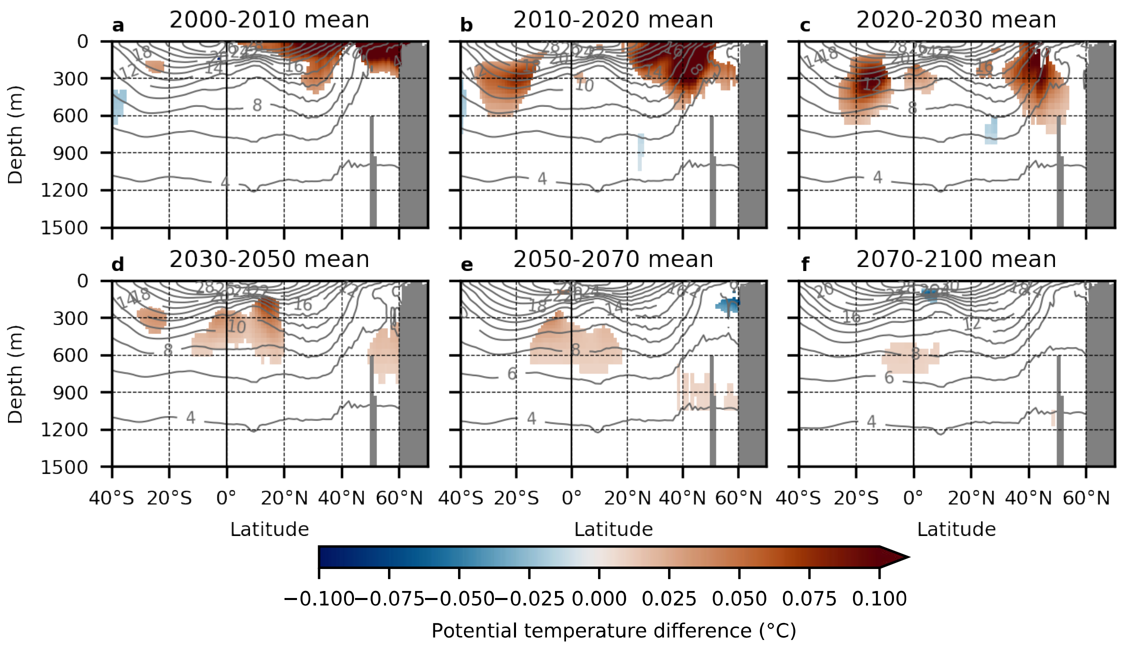

Fig. S6. Difference in CMIP6 and SMBB subensemble means of the Pacific zonal mean temperature over (a) 2000–2010, (b) 2010–2020, (c) 2020–2030, (d) 2030–2050, (e) 2050–2070, and (f) 2070–2100. Climatological mean temperature (100-ensemble mean) over each period is superimposed as contours. Only statistically significant differences at the 95% confidence level are shown.

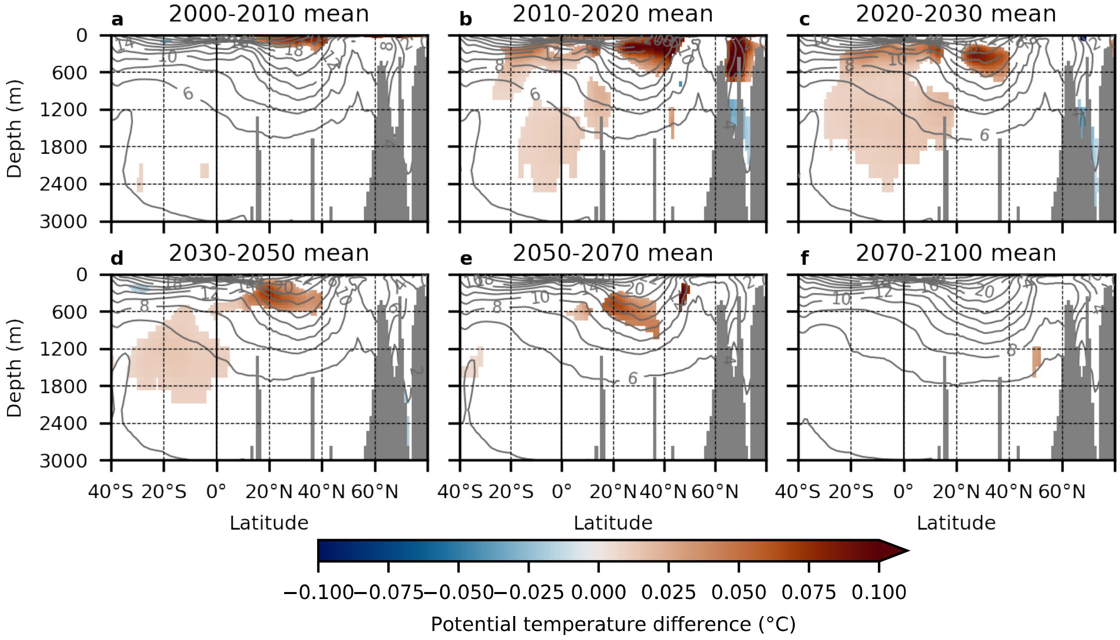

Fig. S7. Difference in CMIP6 and SMBB subensemble means of the Atlantic zonal mean temperature over (a) 2000–2010, (b) 2010–2020, (c) 2020–2030, (d) 2030–2050, (e) 2050–2070, and (f) 2070–2100. Climatological mean temperature (100-ensemble mean) over each period is superimposed as contours. Only statistically significant differences at the 95% confidence level are shown.

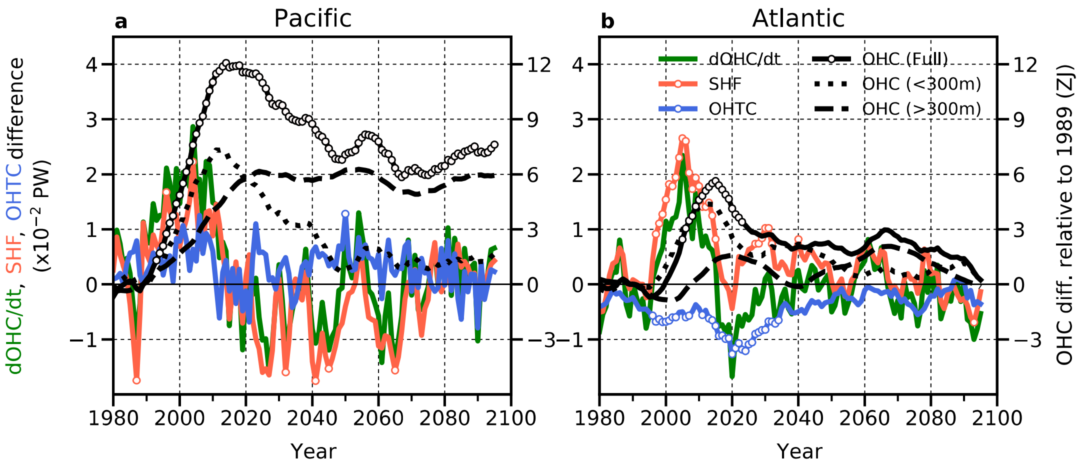

Fig. S8. Same as Fig. 6, but for the whole (a) Pacific and (b) Atlantic. Budgets for the ocean heat content differences between the subensemble means of CMIP6 and SMBB. The 50-50 differences in changes in the full-depth ocean heat content (dOHC/dt), sea surface heat flux (SHF), and ocean heat transport convergence (OHTC) are shown as green, orange, and blue lines with the left y-axis, respectively. Black solid lines are 50-50 differences in the full OHC (with the right y-axis). 50-50 differences in OHCs above 300 m and below 300 m are also shown as dotted and dashed lines with the right y-axis, respectively. An 11-year running mean is applied to all timeseries. The white dots on the black, blue, and orange lines indicate statistically significant differences at the 95% confidence level based on the bootstrapping method. The gray-shaded period corresponds to the time interval where CMIP6 and SMBB forcing are different (1990–2020).