

Supplementary Information for

Drivers and distribution of global ocean heat uptake over the last half century

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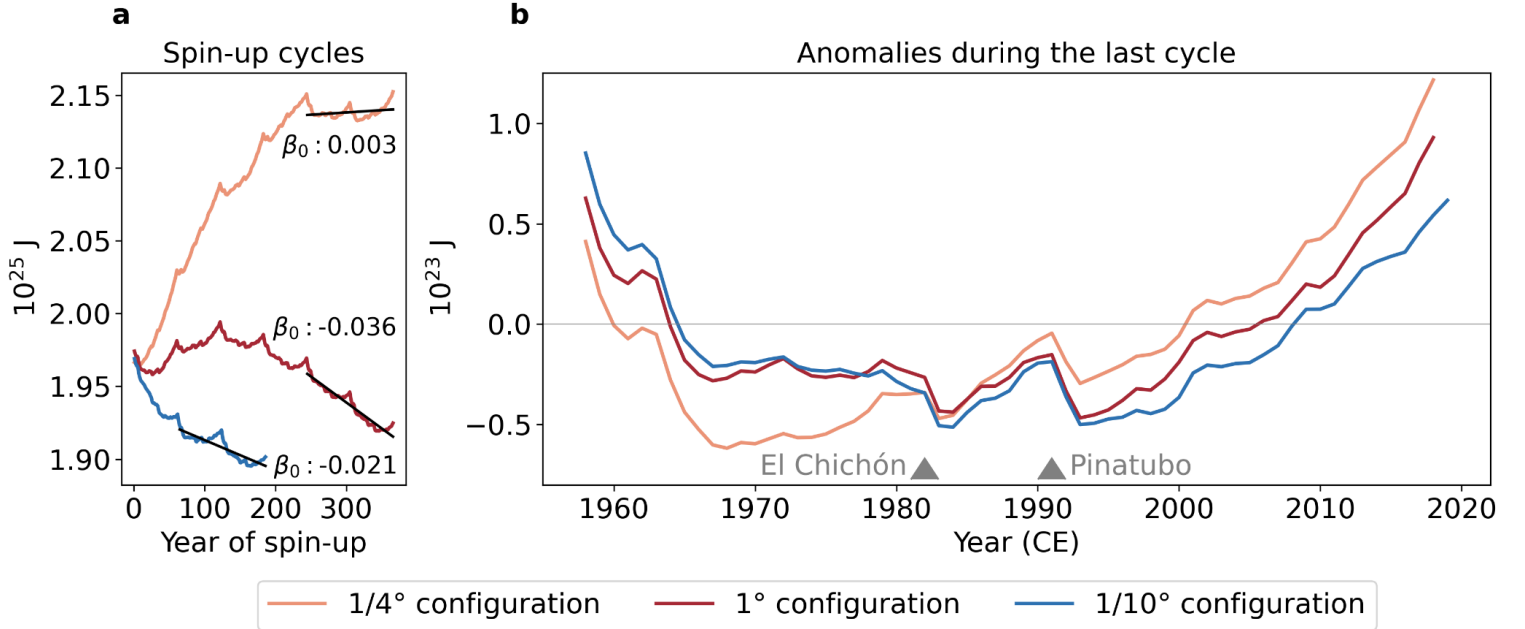
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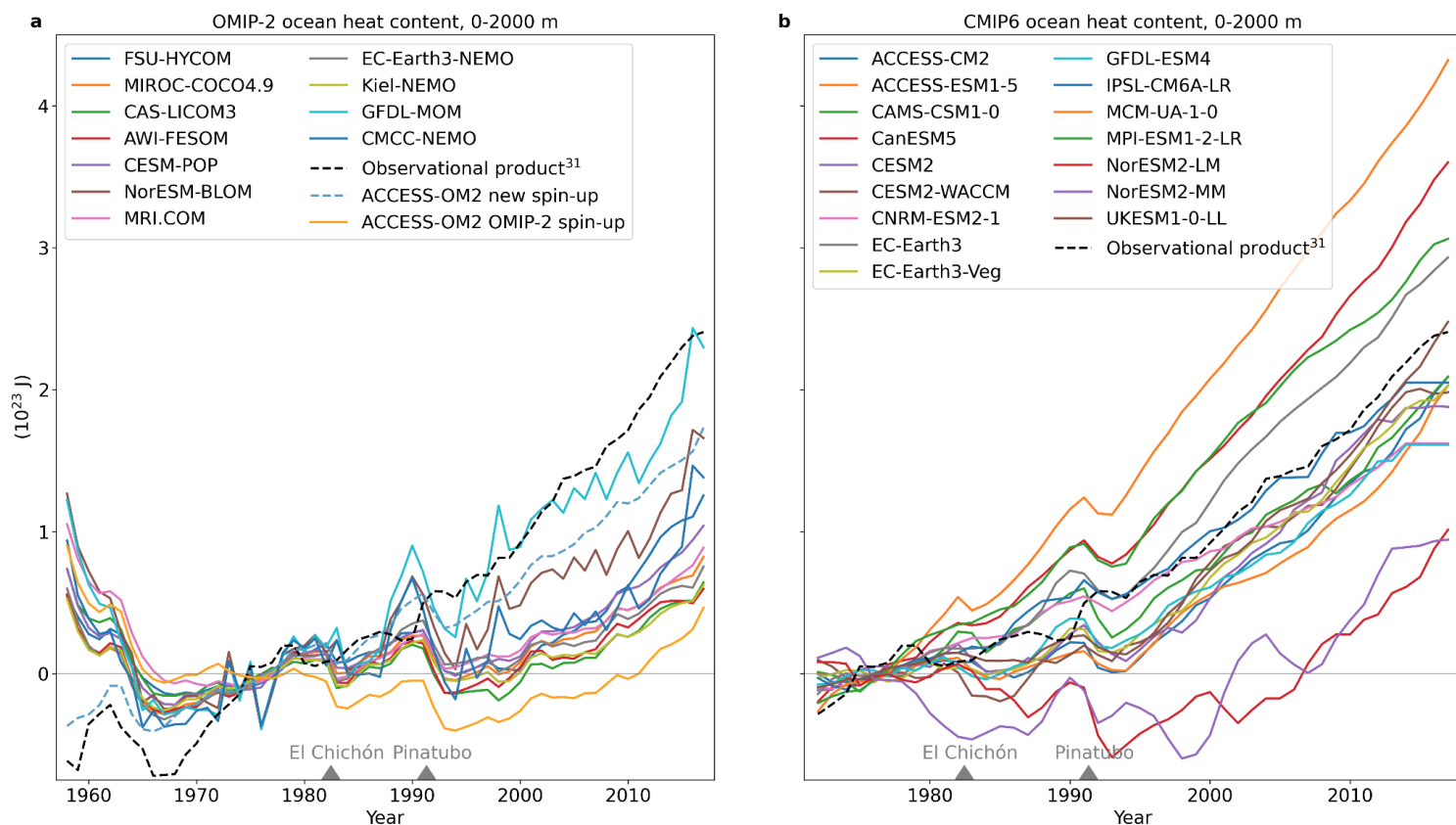
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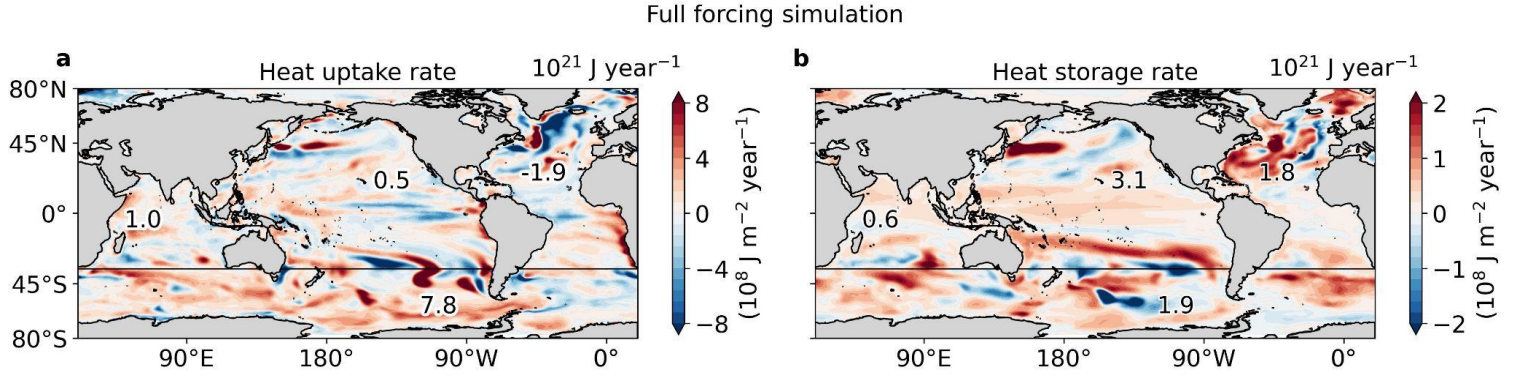
Total ocean heat content in ACCESS-OM2 following OMIP-2



Supplementary Fig. 1. Total ocean heat content anomalies in ACCESS-OM2. **a**, Total ocean heat content (10^{25} J) in the 1°, 1/4° and 1/10° model configuration following the OMIP-2 protocol. Only three spin-up cycles are available in the 1/10° model due to the cost involved in running this configuration. In black the linear trends over the last two cycles with the trend values β_0 in units of 10^{25} J century⁻¹. **b**, Anomalies for the three configurations of the model during the last cycle, calculated by removing the respective linear trend over the last two cycles in **a**.

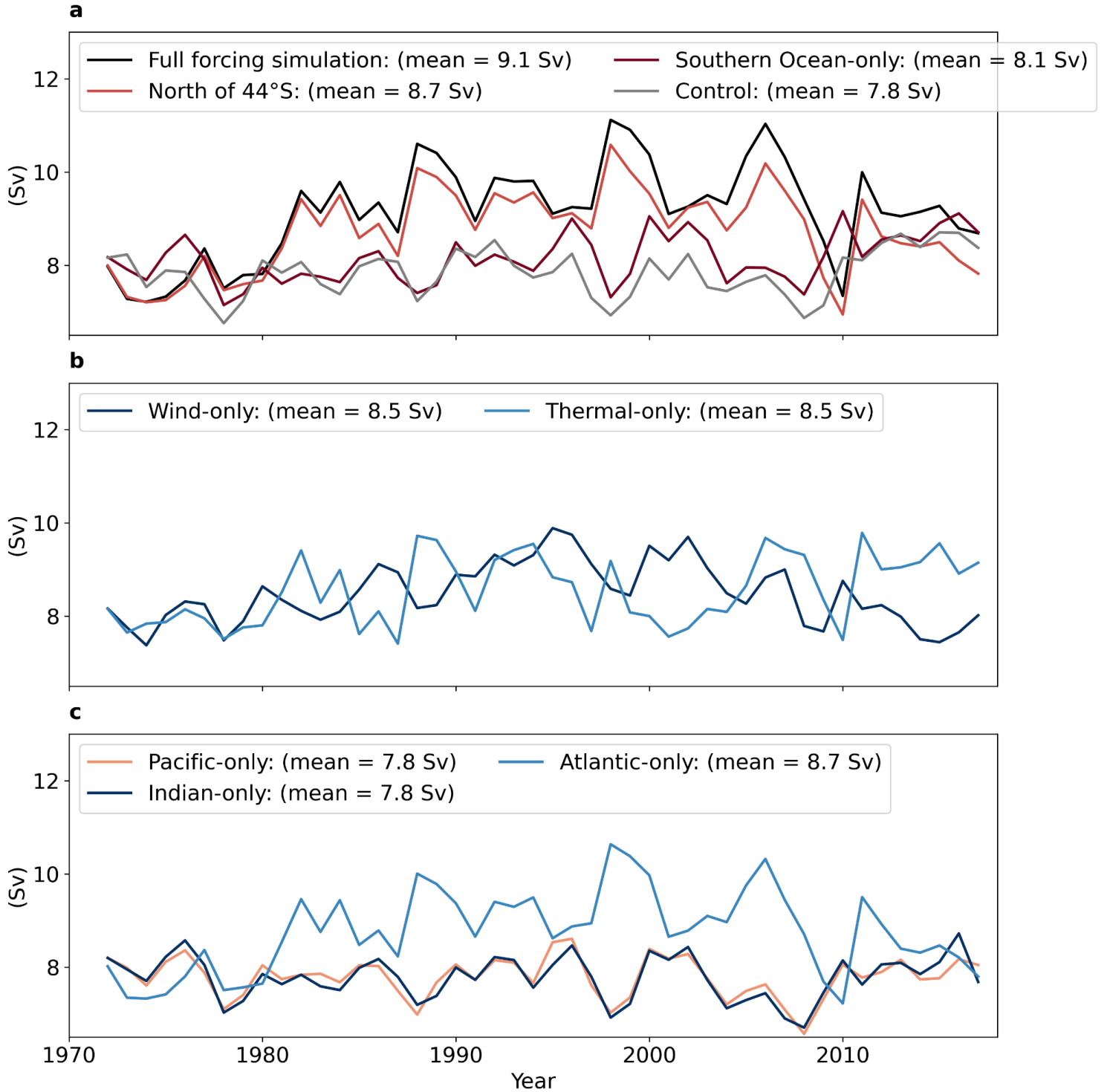


Supplementary Fig. 2. Simulated global ocean heat content in OMIP-2 and CMIP6. **a**, Time series of 1958-2017 OHC anomalies in the eleven OMIP-2 models presented in Tsujino et al. (2020)⁴⁹ and in ACCESS-OM2. The observations from Levitus et al. (2012)³¹ are shown as the dashed black line. The new simulation with full interannual forcing is shown as the dashed blue line. The anomalies are calculated by first removing the linear trend over the last two spin-up cycles and then removing the mean of the 1972-1981 baseline period. **b**, As in **a** but for 25 CMIP6 models²⁵ over 1972-2017.



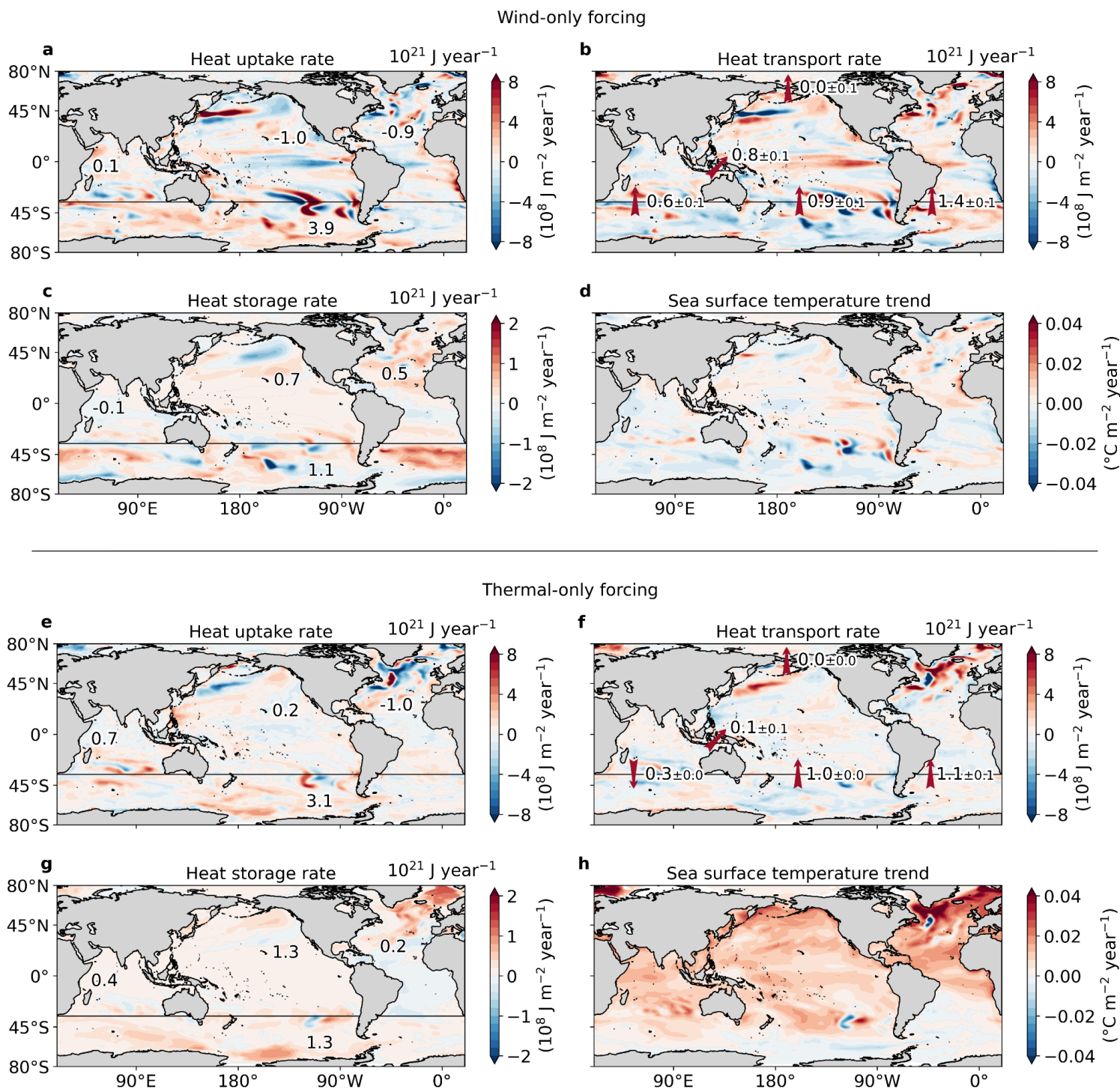
Supplementary Fig. 3. Spatial distribution of ocean heat uptake and storage trends over 1997-2017 in the simulation with full interannual forcing. **a**, Time-integrated net surface heat flux anomalies ($10^8 \text{ J m}^{-2} \text{ year}^{-1}$) with positive heat uptake defined as into the ocean. The basin-wide values ($10^{21} \text{ J year}^{-1}$) show the total area-integrated trends over a particular ocean basin with the boundaries set by the blue lines. The Southern Ocean ends at 36°S , the Bering Strait is at 65°N and the Indonesian Throughflow is defined between Java, New Guinea (105°W to 134°W) at 3°S and the Australian continent (20°S to 6°S) at 137°W . The Atlantic Ocean contributions include the Arctic Ocean north of 65°N and the marginal Hudson Bay, Baltic and Mediterranean basins. The Indian Ocean component also includes the Red Sea. The basin-wide values are rounded to one-decimal point accuracy. **b**, As in **a** but for the heat storage trends.

Maximum AMOC at 26°N, 103°W-5°W



Supplementary Fig. 4. Maximum strength of the Atlantic Meridional Overturning (AMOC) Streamfunction at 26°N between 103°W and 5°W. a, Annual mean upper overturning cell magnitude as a function of time (Sv, 1 Sv = $10^6 \text{ m}^3 \text{ s}^{-1}$), defined as the maximum value of the global overturning streamfunction computed on density surfaces,

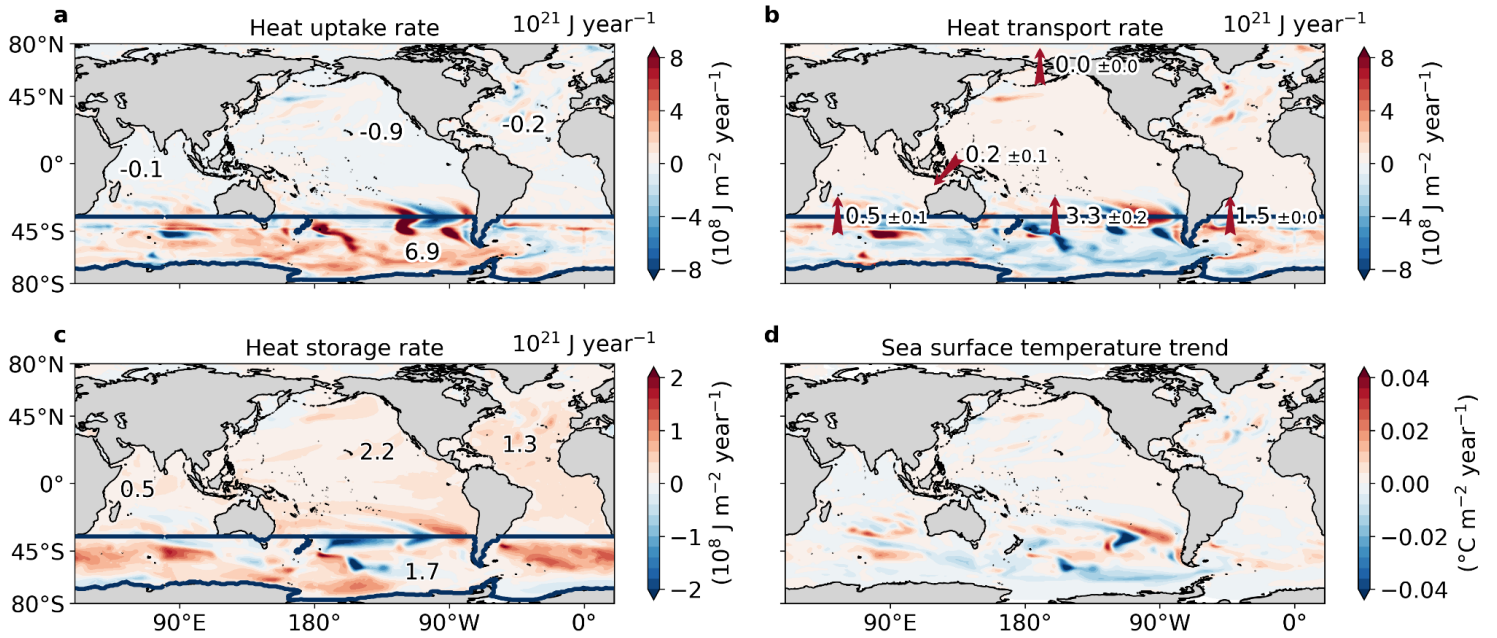
measured at 26° N, integrated between 103° and 5°W and for potential density classes that exceed 1035.5 kg m⁻³. Time series are shown for the full forcing simulation as well as the control simulation, the Southern Ocean-only and the North of 44°S experiments. The mean AMOC strength in these experiments over the full time period is given as the mean for each time series rounded to one decimal point accuracy. **b, c** As in **a** but for the wind- and thermal-only experiments as well as the basin-wide Pacific-, Indian- and Atlantic-only experiments.



Supplementary Fig. 5. Spatial distribution of ocean heat uptake, transport, storage and sea surface temperature trends over 1972-2017 in the wind-only and thermal-only forcing experiment. a, Time-integrated net surface heat flux anomalies ($10^8 \text{ J m}^{-2} \text{ year}^{-1}$) with positive heat uptake defined as into the ocean. The basin-wide values ($10^{21} \text{ J year}^{-1}$) show the total area-integrated trends over a particular ocean basin with the boundaries set by the

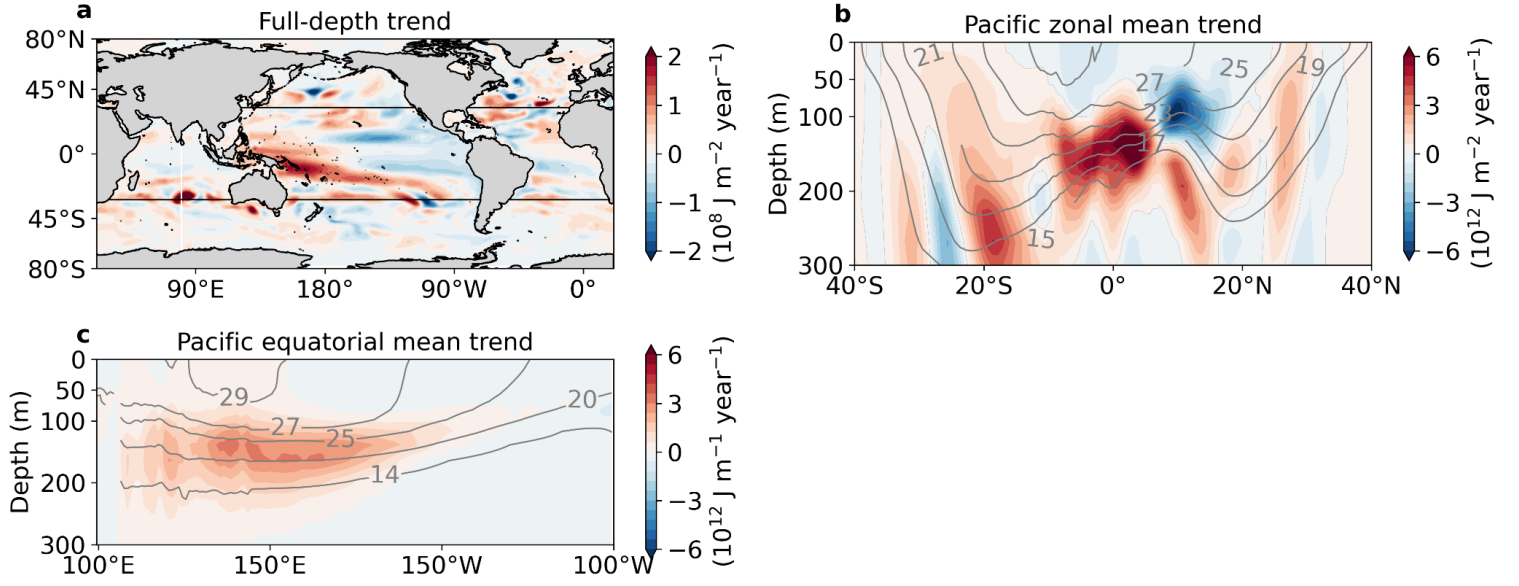
black lines across the Southern Ocean, the Indonesian Throughflow, the Bering Strait and the continental land masses. The Southern Ocean ends at 36°S, the Bering Strait is at 65°N and the Indonesian Throughflow (ITF) is defined between Java, New Guinea (105°W to 134°W) at 3°S and the Australian continent (20°S to 6°S) at 137°W. The Atlantic Ocean contributions include the Arctic Ocean north of 65°N and the marginal Hudson Bay, Baltic and Mediterranean basins. The Indian Ocean component also includes the Red Sea. The basin-wide values are rounded to one-decimal point accuracy. **b**, Anomalous heat transport convergence calculated as a residual from the **a** heat uptake and **c** heat storage ($10^8 \text{ J m}^{-2} \text{ year}^{-1}$). The anomalous heat transport rates and their uncertainties across transects ($10^{21} \text{ J m}^{-2} \text{ year}^{-1}$) are calculated from anomalous heat and volume transports (see Methods). **d**, Simulated SST trends ($^{\circ}\text{C m}^{-2} \text{ year}^{-1}$). Grid cells in **d** that have a climatological sea ice coverage above 85% have been removed and are shaded white. **e-f**, As in **a-d** but for the perturbation experiment where only atmospheric trends in thermal properties are applied (surface air temperature, humidity, radiation, precipitation and sea level pressure trends, while repeat decade forcing is used for the other forcing fields).

Southern Ocean-only forcing

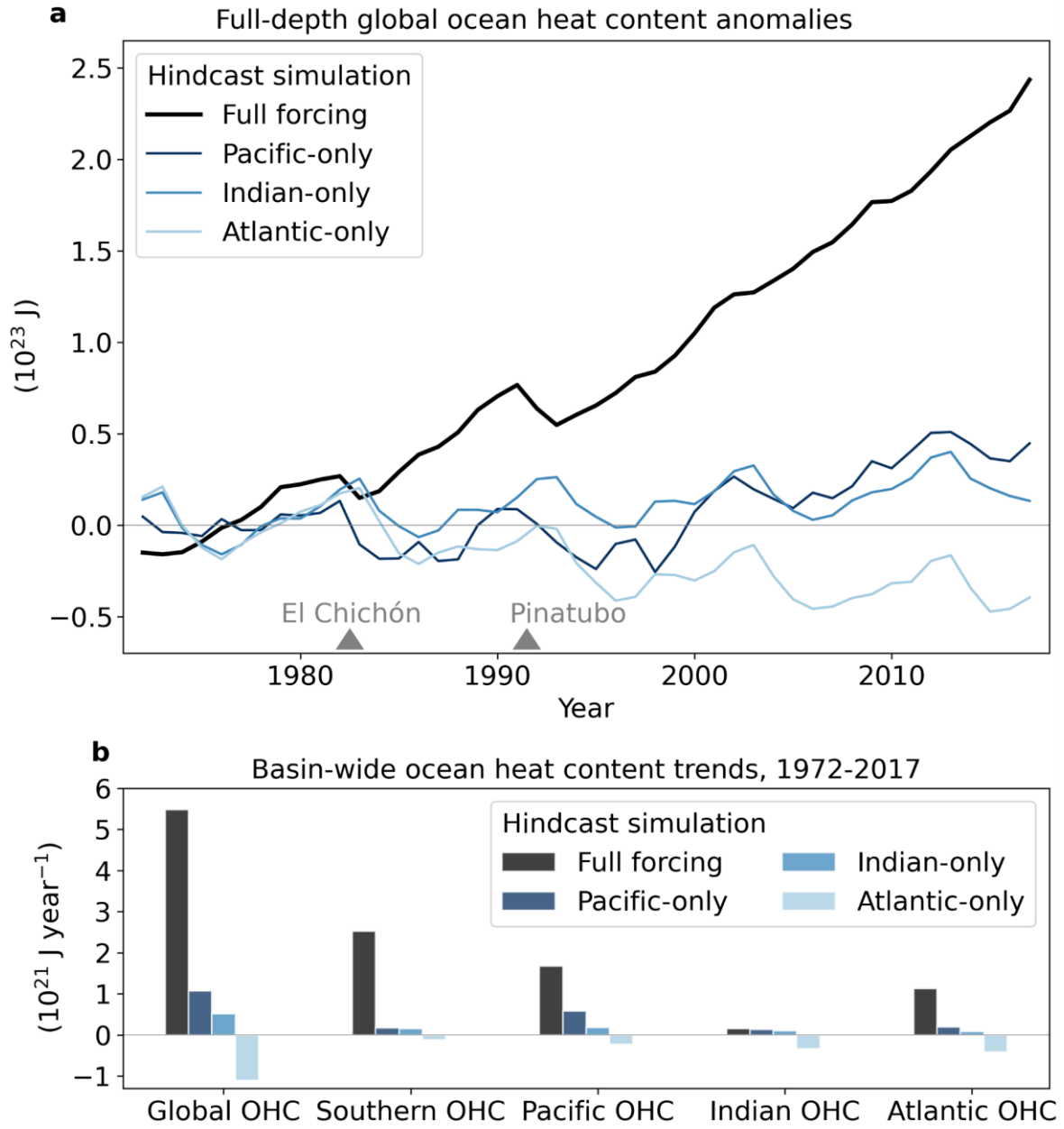


Supplementary Fig. 6. As in Supplementary Fig. 5 but for the Southern Ocean experiment where interannual forcing is applied south of 44°S over the region with blue outlines. Repeat decade forcing is applied north of 40°S and the tapering zone between the two forcing fields is from 44°S to 40°S .

Tropics-only 30°S-30°N ocean heat content trends, 1992-2011

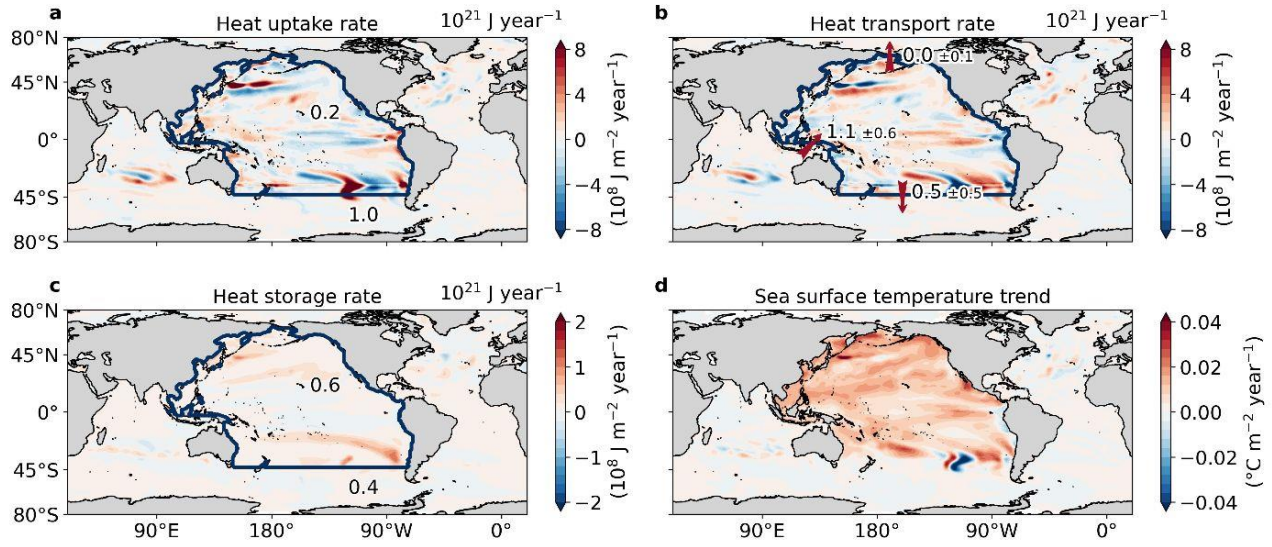


Supplementary Fig. 7. Ocean heat content trends over 1992-2011 in the Tropics-only 30°S-30°N experiment. a, Spatial pattern of anomalous ocean heat content trend over 1992-2011 ($10^8 \text{ J m}^{-2} \text{ year}^{-1}$). The horizontal blue lines indicate the region over which interannual forcing is applied (30°S-30°N). **b,** Zonal mean ocean heat content trends in the Pacific Ocean 100°E-100°W ($10^{12} \text{ J m}^{-2} \text{ year}^{-1}$). The contours show the climatological isotherms across the Pacific 40°S-40°N (°C). **c,** Equatorial mean 5°S-5°N ocean heat content trends in the Pacific Ocean ($10^{12} \text{ J m}^{-2} \text{ year}^{-1}$). The contours show the climatological isotherms across the Pacific 100°E-100°W (°C).

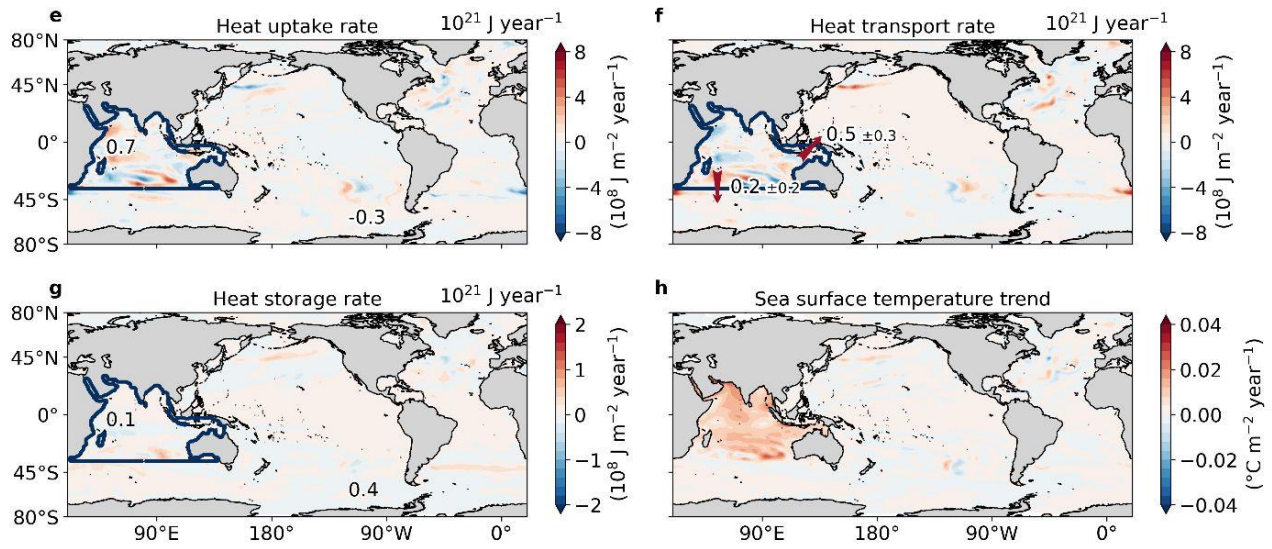


Supplementary Fig. 8. Ocean heat content changes since 1972 in the basin-wide simulations. **a**, Time series of the full-depth ocean heat content anomalies where interannual forcing is applied only over the Pacific, Indian and Atlantic basins compared with the simulation where interannual forcing is applied over the full ocean area ($10^{21} \text{ J year}^{-1}$). For the Pacific Ocean simulation, we choose the southern interannual forcing/repeat decade forcing boundary at 44°S as this latitude marks the poleward extent of the shallow subtropical cells. For the Indian and Atlantic Ocean simulations, we set the boundary to 35°S at the southern tip of Africa. **b**, The basin-integrated ocean heat content trends for the perturbation experiments in **a** with the boundaries set by the dark blue lines in Fig. 2 in the main manuscript.

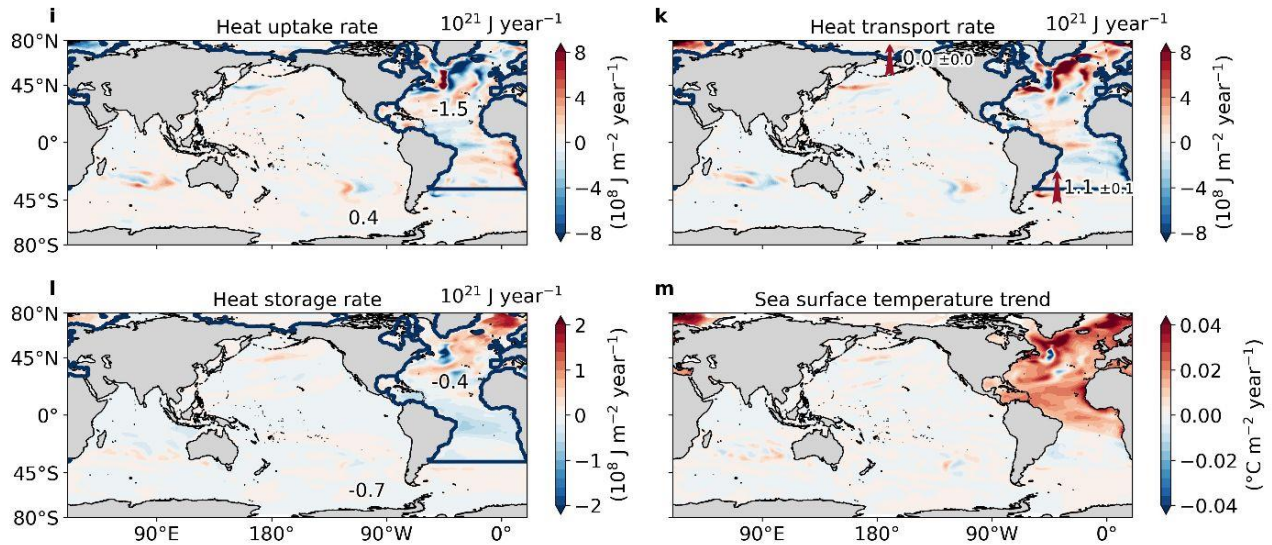
Pacific Ocean-only forcing



Indian Ocean-only forcing



Atlantic Ocean-only forcing



Supplementary Fig. 9. As in Supplementary Fig. 5 but for the **a-d** Pacific Ocean-only, **e-h** Indian Ocean-only and **i-m** Atlantic Ocean-only forcing experiment. The blue outlines indicate the region over which interannual forcing is applied while repeat decade forcing is used over the remaining ocean area.

	Net shortwave heat flux	Net longwave heat flux	Sensible heat flux	Latent heat flux
Full forcing simulation	0.1	3.1	3.3	-0.3
Wind-only forcing	0.6	1.9	3.7	-2.7
Thermal-only forcing	0.1	3.0	2.4	-3.1

Supplementary Table. 1. Heat flux contributions to anomalous Southern Ocean heat uptake. Contributions of the basin-wide integrated heat flux trends over the Southern Ocean south of 36°S in the simulation with full interannual forcing, with wind-only forcing and thermal property-only forcing (10^{21} J year⁻¹). The values are rounded to one-decimal point accuracy. Only the four major heat flux components are shown here without the surface flux contributions from surface volume exchanges and heat exchanges with sea ice.

Model acronym	Ensemble member	Reference
ACCESS-CM2	r1i1p1f1	Dix et al. (2019a, 2019b, 2019c)
ACCESS-ESM1-5	r1i1p1f1	Ziehn et al. (2019a, 2019b, 2019c)
CAMS-CSM1-0	r1i1p1f1	Rong (2019a, 2019b, 2019c)
CanESM5	r1i1p1f1	Swart et al. (2019a, 2019b, 2019c)
CESM2	r1i1p1f1	Danabasoglu (2019, 2019a, 2019b)
CESM2-WACCM-FV2	r1i1p1f1	Danabasoglu (2019c, 2019d, 2019e)
CESM2-WACCM	r1i1p1f1	Danabasoglu (2019f, 2019g, 2019h)
CNRM-ESM2-1	r1i1p1f2	Seferian (2018a, 2018b), Voldoire (2019)
EC-Earth3	r1i1p1f1	EC-Earth (2019a, 2019b, 2019c)
EC-Earth3-Veg	r1i1p1f1	EC-Earth (2019d, 2019e, 2019f)
GFDL-ESM4	r1i1p1f1	Krasting et al. (2018a, 2018b), John et al. (2018)
IPSL-CM6A-LR	r1i1p1f1	Boucher et al. (2018a, 2018b, 2019a)
MCM-UA-1-0	r1i1p1f1	Stouffer (2019a, 2019b)
MPI-ESM1-2-LR	r1i1p1f1	Wieners et al. (2019a, 2019b, 2019c)
NorESM2-LM	r1i1p1f1	Seland et al. (2019a, 2019b)
NorESM2-MM	r1i1p1f1	Bentsen et al. (2019a, 2019b, 2019c)
SAM0-UNICON	r1i1p1f1	Park and Shin (2019a, 2019b)
UKESM1-0-LL	r1i1p1f2	Tang et al. (2019a, 2019b), Good et al. (2019)

Supplementary Table. 2. CMIP6 GCM ensemble model information. For a list of the model acronyms, see <http://www.ametsoc.org/PubsAcronymList>.

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