Supplementary Information

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Enhanced hydrological cycle increases ocean heat uptake and moderates transient climate sensitivity

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This file includes:
Supplementary Texts
Supplementary texts 1-2

Supplementary Figures
Supplementary Figures 1 to 20

Supplementary Tables
Supplementary Table 1
Supplementary Texts

Supplementary Text 1: The climatological effect of fixing SSS on the control simulations

Difference in the model response to the CO$_2$ forcing between the STD and fixed-SSS-GL experiment is affected by the climatological effect of fixing SSS on the control simulations. We quantify this effect in terms of global mean surface temperature, net radiation at the top-of-atmosphere (TOA) and ocean heat content (OHC) by comparing 100 model years of the control run from the two model versions.

As shown in Supplementary Fig. 1, global mean surface temperature from the fixed-SSS-GL run has a lower variability than the STD run in terms of the whiskers, likely because fixing SSS inhibits the internal variability. However, the mean and median surface temperature from the two runs are quite close. In addition, based on the Student’s two-sided t-test ($p = 0.88$), there is no statistically significant difference in the surface temperature samples from the two control runs. In addition, the CO$_2$ response difference in terms of transient climate response (TCR) between the STD and fixed-SSS-GL version reaches -0.4 K, two orders of magnitude larger than the mean difference (0.002 K) between the two versions from the control simulation.

To examine the impact of the temporal variation in the control runs on the TCR difference between the STD and fixed-SSS-GL version, we computed TCR based on a simulation length ranging from 70 to 95 years with an interval of 5 years from the control run, which results in 105 samples of TCR. The mean and standard deviation of the TCR difference from these samples are 0.392 K and 0.009 K, respectively. The minimum and maximum TCR difference are 0.370 and 0.414 K, respectively. These results further demonstrate that the temporal variation in the control runs has relatively small impact on the TCR difference.

Similar to the global mean surface temperature, there is no statistically significant difference in net radiation at the TOA ($p = 0.84$) and OHC ($p = 0.85$) from the 100-yr control runs of the STD and fixed-SSS-GL version based on the Student’ t-test. In addition, the mean and median values, as shown in Supplementary Fig. 2, are similar between the two experiments. In addition, the difference in the mean value (-0.013 W m$^{-2}$ for net radiation at the TOA and 0.007 10$^{24}$ J for OHC) is much smaller than that in response to CO$_2$ doubling (0.189 W m$^{-2}$ for net radiation at the TOA and 0.102 10$^{24}$ J for OHC).

To explore the impact of the temporal variation, we repeated the Student’ two-sided t-test based on a simulation length ranging from 70 to 95 years with an interval of 5 years. For the net radiation at the TOA, the minimum and maximum p-value are 0.51 and 0.99, respectively with a mean of 0.81. For the OHC, the minimum and maximum p-value are 0.70 and 0.90, respectively with a mean of 0.78. These results suggest that shortening the length of the simulation has little influence.
on the argument that there is no statistically significant difference in both net radiation at the TOA and OHC between the STD and fixed-SSS-GL run.

Supplementary Text 2: Transient climate feedback from the STD and fixed-SSS-GL version
The STD and fixed-SSS-GL version show similar transient climate feedback (-1.55 versus -1.45 W m\(^{-2}\) K\(^{-1}\); Supplementary Table 1) computed using the radiative kernel method\(^1\) (see Methods for details). The slightly lower (less negative) transient climate feedback in the fixed-SSS-GL run relative to the STD run is dominated by the lapse rate feedback (-0.73 versus -0.59 W m\(^{-2}\) K\(^{-1}\); Supplementary Table 1). The increased warming in the fixed-SSS-GL run over the STD run is more pronounced at high latitudes than low latitudes (Supplementary Fig. 2), resulting in a smaller reduction in lapse rate and thus a smaller (less negative) lapse rate feedback\(^2\). The slightly lower contrast in total climate feedback than the lapse rate feedback between the two model versions is likely attributed to the offsetting effect between lapse rate feedback and water vapor feedback\(^2\) (Supplementary Table 1).

Reference:
1. Soden, B. J. \textit{et al.} Quantifying Climate Feedbacks Using Radiative Kernels. \textit{J. Clim.} \textbf{21}, 3504–3520 (2008).
2. Soden, B. J. & Held, I. M. An assessment of climate feedbacks in coupled ocean-atmosphere models. \textit{J. Clim.} \textbf{19}, 3354–3360 (2006).
Supplementary Fig. 1. **Comparison of surface temperature between the STD and fixed-SSS-GL control simulation.** Boxplot of the annual global-mean surface temperature from the 100-yr control run of both the STD and fixed-SSS-GL model version. The black dots indicate the mean of all surface temperature samples. The black boxes range from the 25th quartile to 75th quartile. The orange line in the box indicates the median. The whiskers extend out to the largest and smallest values within 1.5 times the interquartile range (difference between the 75th and 25th percentiles).
Supplementary Fig. 2. The response of surface warming to transient CO$_2$ doubling. 

a. The change in the spatial pattern of surface temperature in response to CO$_2$ doubling for the STD version. 

b. The difference in the response of surface temperature to CO$_2$ doubling between the fixed-SSS-GL and STD version.
Supplementary Fig. 3. **Comparison of net radiation at the top-of-atmosphere (TOA) and ocean heat content (OHC) between the STD and fixed-SSS-GL control simulation.** Same as Supplementary Fig. 1 but for **a** net radiation at the TOA and **b** OHC.
Supplementary Fig. 4. **Surface buoyancy flux.** a, the response of heat-equivalent buoyancy flux (W m$^{-2}$) to CO$_2$ doubling in the STD version. b, Difference in the response of heat-equivalent buoyancy flux between the fixed-SSS-GL and STD version. c, Same as b, but for heat-equivalent freshwater flux.
Supplementary Fig. 5. The climatology of precipitation (P) minus evaporation (E). The climatology of P-E (mm d\(^{-1}\)) from the 100-year control run of the STD version.
Supplementary Fig. 6. **Zonal velocity in the ocean.** a-c, The climatology of zonal velocity (m s\(^{-1}\)) from the 100-year control run of the STD version at different ocean depth. d-f, Difference in the response of zonal velocity to the CO\(_2\) doubling between the STD and fixed-SSS-GL version.
Supplementary Fig. 7. Same as Fig. 3, but for the Pacific and Indian Ocean. The area of the Non-Atlantic Ocean is indicated in Fig. 3a.
Supplementary Fig. 8. **The strength of AMOC at 40°N.** The streamfunction of AMOC (Sv) as a function of depth at 40°N for all FLOR runs. The control runs use model year 101-200 while the transient CO₂ runs use model years 161-180 centered on the year when CO₂ first doubles (year 170).
Supplementary Fig. 9. **Ocean basins with fixed SSS for the fixed-SSS-subAtl version.** The subtropical Atlantic Ocean with fixed SSS is masked in orange.
Supplementary Fig. 10. Same as Fig. 3, but for the FLOR experiments with fixed SSS in the subtropical Atlantic as indicated in Supplementary Fig. 6 (the fixed-SSS-subAtl version).
Supplementary Fig. 11. Impact of fixing SSS in subtropical Atlantic (fixed-SSS-subAtl) on the response of OHC to CO₂ doubling. Difference in the response of OHC (10⁹ J m⁻²) to CO₂ doubling between the STD and fixed-SSS-subAtl version. The difference is computed using years 161-180 for the CO₂ run and years 101-200 for the control run.
Supplementary Fig. 12. **Impact of fixing SSS in subtropical Atlantic (fixed-SSS-subAtl) on the response of Atlantic subsurface salinity to CO₂ doubling.** Difference in the response of zonal-integral ocean salinity ($10^6$ psu·m) between the fixed-SSS-GL and fixed-SSS-subAtl version in the Atlantic Ocean.
Supplementary Fig. 13. Same as Supplementary Fig. 6, but for the fixed-SSS-nonAtl version.
Supplementary Fig. 14. Same as Fig. 3, but for the FLOR experiments with fixed SSS in the non-Atlantic Ocean as indicated in Supplementary Fig. 13 (the fixed-SSS-nonAtl version).
Supplementary Fig. 15. Same as Supplementary Fig. 14, but for the Pacific and Indian Ocean. The area of the Non-Atlantic Ocean is indicated in Fig. 14a.
Supplementary Fig. 16. **The linear trend of sea surface salinity from observation-constrained datasets.** The linear trend (psu/50yr) of sea surface salinity over the period of 1968-2017 from a NCEI, b JMA, c IAP, and d ORAS4 data. The trend is tuned by the ratio of CO$_2$ concentration at CO$_2$ doubling in FLOR to that in 2017 from observations. The area with statistical significance (p < 0.05) is stippled.
Supplementary Fig. 17. Same as Fig. 5, but for JMA data.
Supplementary Fig. 18. Same as Fig. 5, but for IAP data.
Supplementary Fig. 19. Same as Fig. 5, but for ORAS4 data.
Supplementary Fig. 20. The annual CO₂ concentration (ppm) on the global scale (red) and in Mauna Loa, Hawaii (blue) over the period of 1968-2017.
Supplementary Table 1. Transient radiative feedbacks (W m\(^{-2}\) K\(^{-1}\)) from both the STD and fixed-SSS-GL version during the CO\(_2\) stabilization period (year 161-180) calculated using radiative kernels.

|                | Planck | Lapse rate | Water vapor | Albedo | Cloud | Total  |
|----------------|--------|------------|-------------|--------|-------|--------|
| STD            | -3.31  | -0.73      | 1.85        | 0.30   | 0.35  | -1.55  |
| Fixed-SSS-GL   | -3.30  | -0.59      | 1.77        | 0.31   | 0.38  | -1.45  |