# Supplementary Information for 'Hydrological cycle amplification overwhelms warming-driven oxygen loss in subsurface Atlantic Ocean'

Allison Hogikyan[a] Laure Resplandy[b,c] Maofeng Liu [d] Gabriel Vecchi[a,b,c]

[a] *Atmospheric and Oceanic Sciences Program, Princeton University*
[b] *Geosciences Department, Princeton University*
[c] *High Meadows Environmental Institute, Princeton University* [d] *University of Miami Rosenstiel School of Marine, Atmospheric, and Earth Science*

*Corresponding author*: A. Hogikyan, hogikyan@princeton.edu

## 1. Temperature trend in the Atlantic Ocean at 25°W

The Atlantic Ocean warms in both the observation-based reanalysis ORAS5 (1958-2017) and the ESM2M model (200-year trend in Standard experiments) (Figure S1a, b), with the exception of the North Atlantic around 50°N, which cools in ESM2M and has no temperature change in ORAS5. This lack of warming is consistent with the slight weakening of the Atlantic Meridional Overturning Circulation and associated decrease in northward heat transport and local cooling ('warming hole,' Drijfhout et al. 2012). The hydrological effect alone in ESM2M (difference between Standard and Fix-SSS experiments) acts to enhance ocean warming below about 500-700m depth but weaken warming above (Figure S1c), consistent with prior studies (Liu et al. 2021; Williams et al. 2007). This surface cooling explains the increased $\Delta O_{2Hydro,sat}$ in Tropical Waters (see Figure 4 and Section 4 in main text).

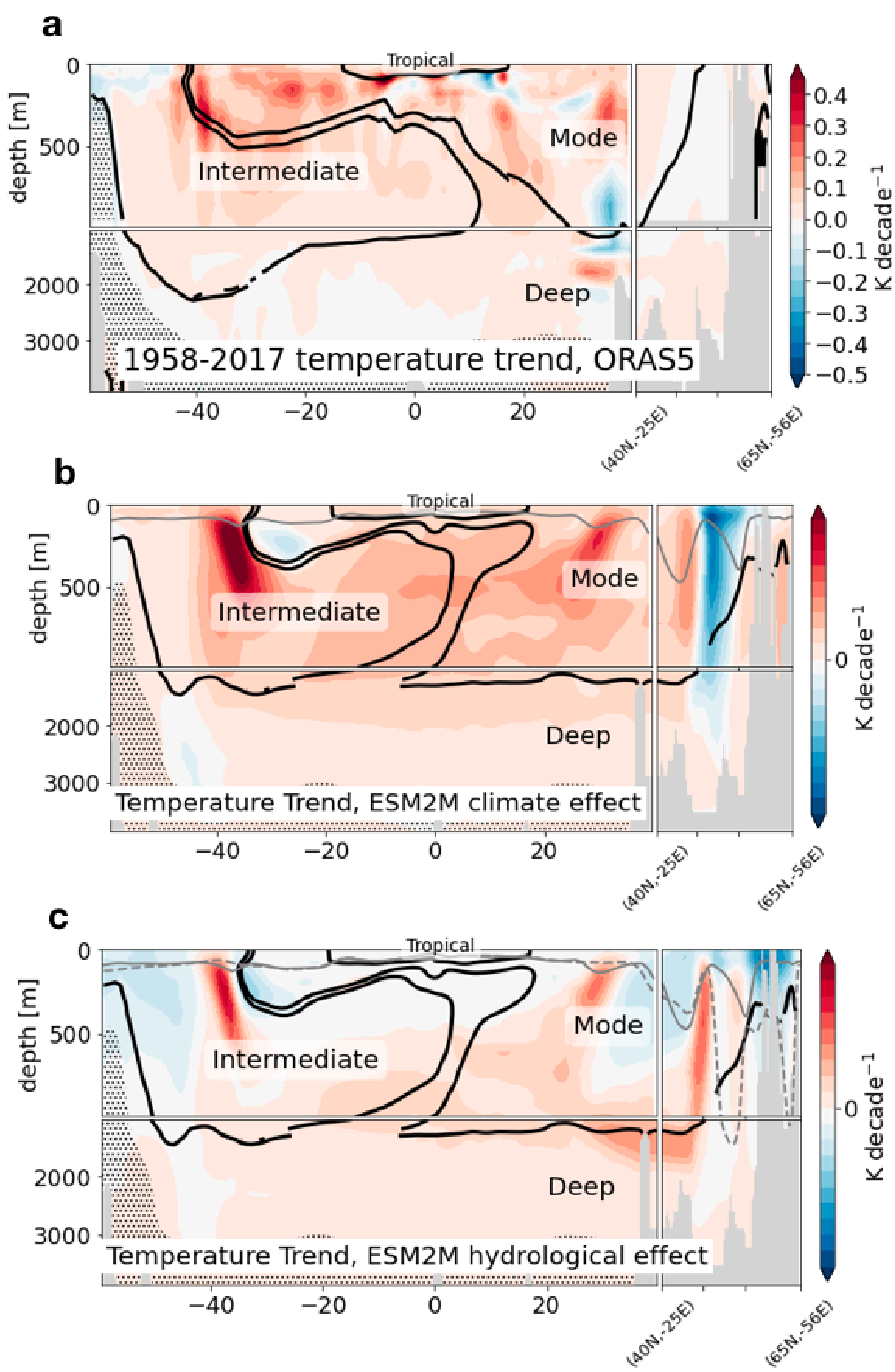



Figure S1. **Warming along mid-Atlantic Ocean section.** (a) ORAS5 historical temperature trend (1958-2017), (b) ESM2M temperature trend due to total climate effect (200-year trend in the Standard experiment, averaged across 5 members), (c) ESM2M temperature trend due to hydrological effect (Difference in 200-year trends between the Standard and Fix-SSS experiments, averaged over 5 members for each experiment).

## 2. Contribution of precipitation, evaporation, ice melt to sea surface salinity trends

The future projection of a ‘salty-get-saltier and fresh-get-fresher’ SSS trend is based on the expected evolution of the net air-sea freshwater flux (Bindoff et al. 2019) but does not specify the relative contribution of changes in evaporation vs. changes in precipitation. We qualitatively assess trends in evaporation and precipitation (liquid and frozen) as well as the contribution of sea ice melt and freshwater input from land (calving+runoff) which can reinforce or offset the amplification of SSS patterns expected from evaporation and precipitation (Figure S2a-d). The strong subtropical SSS increase which increases the ventilation of Mode Waters (Figure 1) is driven by an increase in evaporation and partly opposed by an increase in precipitation (Figure S2a-c). We note that the clear increase in precipitation in the equatorial band (which is expected from the evaporation-precipitation amplification argument) does not yield a significant freshening (Figure 1), most likely due to the advection of saltier water from the subtropics by the mean circulation. At higher latitudes, the freshening is driven by a decrease in evaporation in the northern hemisphere where Deep Waters outcrop (although precipitation changes modulate the the zonal pattern of SSS change). In contrast, the surface freshening in the southern hemisphere where Intermediate Waters outcrop is associated with a precipitation increase.

Long-term trends in ice melt, runoff, and calving do not strongly affect the modeled SSS trends, since they are dominated by the retreat of the sea ice edge (i.e. change in location of freshwater input) rather than a secular increase or decrease in freshwater input (brown/green dipole in the Labrador and Irminger Seas, and Weddell Gyre, Figure S2d). In fact, the North Atlantic freshening is locally opposed by a decrease in freshwater input from ice melt, calving, and runoff (>50°N; grey in Supplemental Figure 2e). However, melt water from long-term sea ice loss in the Arctic (>70°N) could be transported south and enhance the North Atlantic freshening. Similarly, in the South Atlantic, the sea ice edge retreat leads to a strongly offsetting positive and negative freshwater flux trend, which we expect has a small effect on salinity trends in Intermediate Waters.

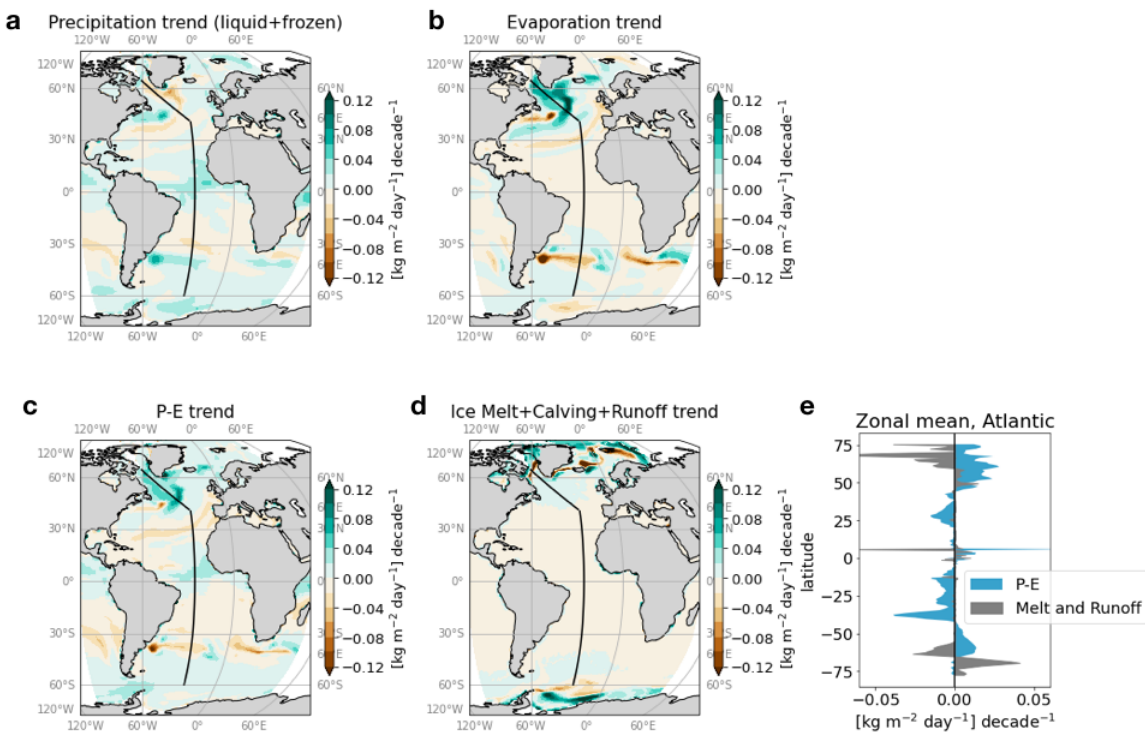



Figure S2. **Freshwater flux trends in response to $CO_2$ forcing.** 200-year freshwater flux trends in the Standard 1%-to-doubling experiment.

## 3. Ventilation changes in climate effect largely attributed to hydrological effect

Figure 3a in the main text compares the total oxygen changes due to the climate effect and hydrological effect while Figure 3b breaks down the oxygen change due to the hydrological effect in terms of contributions from ventilation, saturation, and biology ($\Delta O_{2Hydro,vent}$, $\Delta O_{2Hydro,sat}$, $\Delta O_{2Hydro,bio}$). Here, in Figure S3 we provide the contributions from ventilation, saturation, and biology to the climate effect. We note in particular that the increased ventilation due to the hydrological effect in Mode Waters appears to drive a similar ventilation increase in Mode Waters in the total climate effect. This hydrological cycle - driven ventilation increase is opposed by the decline in solubility of oxygen, so that there is no net change in oxygen in Mode Waters in the climate effect. Similarly, the decreased ventilation in Deep Waters due to the hydrological effect appears to explain much of the ventilation decrease in the total climate effect. In the total climate effect, the ventilation decline doubles the oxygen loss due to solubility alone. Illustrative visual sections through the mid-Atlantic Ocean showing the total response of oxygen to the climate effect

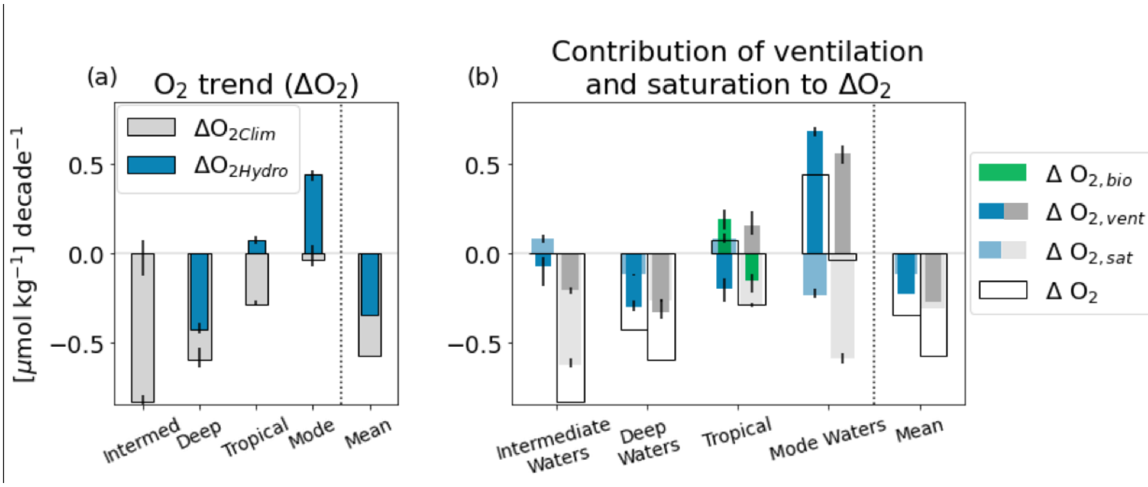
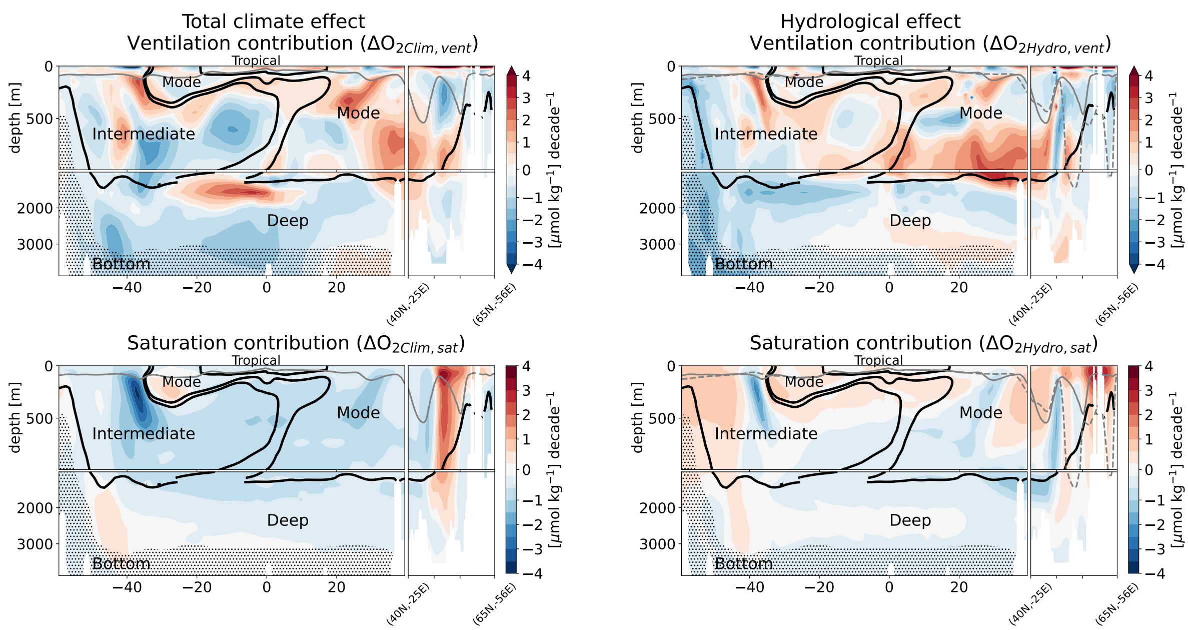



Figure S3. **Mean trends in (de)oxygenation and drivers.** (a) Ensemble mean change in oxygen in Atlantic Ocean water masses due to climate effect (grey) and hydrological effect (blue), as in Figure 4a. (b) Contribution of ventilation (bold) and saturation (faded) to climate effect (grey) and hydrological effect (blue). Contribution of biological activity to climate effect and hydrological effect is also shown in green. Black outlines indicate the total oxygen change in panel (a), which is the sum of the three components. Error bars represent the range across five ensemble members.

and the hydrological effect, are provided in the main text (Figure 3). Here in Figure S4 we provide visuals along the same section of the contributions from $\Delta O_{2Clim,vent}$ and $\Delta O_{2Clim,sat}$, as well as $\Delta O_{2Hydro,vent}$ and $\Delta O_{2Hydro,sat}$.

## 4. Masks for SSS restoring setup and Atlantic Ocean analysis

In this study, we link the robust ’salty-get-saltier, fresh-get-fresher’ SSS trend patterns to ocean ventilation and oxygen content by restoring SSS to its pre-industrial climatological values. The thermodynamic argument supporting the amplification of the hydrological cycle does not apply to changes in freshwater flux tied to seasonal sea ice formation and melt, and how they would evolve in response to warming. Consequently, the SSS restoring is only applied to regions that do not experience seasonal sea ice in our pre-industrial control experiment (light blue color in Figure S5). The mask used to define the Atlantic Ocean in this study is based on the ‘regionmask’ Python package and shown by the darker blue area in Figure S5.




73 Figure S4. **(De)oxygenation due to ventilation change and saturation change along Atlantic Ocean**
74 **section.** The contributions of ventilation and saturation to the oxygen changes in Figure 3 c, d.

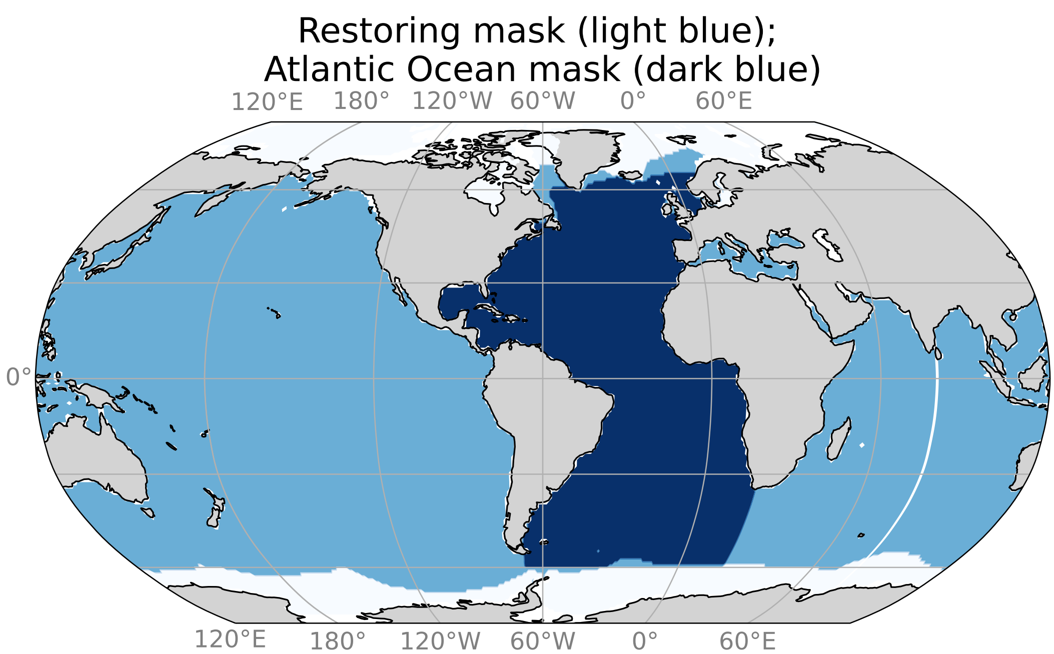



Figure S5. **Mask of SSS restoring location, and Atlantic Ocean.** Global restoring of sea surface salinity is only applied in the light and dark blue locations, but is not applied where there is seasonal sea ice in pre-industrial control run (white regions). Dark blue mask based on 'regionmask' Python package is used to isolate Atlantic Ocean water masses in Figures 2,4, and Supplemental Figure S3.

## References

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