Anthropogenic aerosols offsetting ocean warming less efficiently since the 1980s

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Introduction

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This document outlines the models and ensembles members used in this study, and explores the detailed, process-based analysis of the heat budget in a single CMIP6 model - ACCESS-CM2.

Text S1 provides specific information on the CMIP6 models and ensemble members studied (as shown in Table S1). Text S2 investigates the contribution of explicitly calculated mixing and surface heat flux terms to the overall heat budget in ACCESS-CM2, as shown in Figure S1.

Text S1.

Table S1 provides a summary of the CMIP6 modelling groups and ensemble members that were analysed in this study. For all models and ensemble members, the *hist-nat*, *hist-GHG*, *hist-aer*, *piControl* and *historical* experiments were analysed.

	Model Name	Ensemble Members
1	ACCESS-CM2	rxi1p1f1, where $x = 1, 2, 3$
2	ACCESS-ESM1-5	rxi1p1f1, where $x = 1, 2, 3$
3	CESM2	rxi1p1f1, where $x = 1, 3$
4	CNRM-CM6-1	rxi1p1f2, where $x = 1, 2, 3$
5	CanESM5	rxi1p1f1, where $x = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15$
6	HadGEM3-GC31-LL	rxi1p1f3, where $x = 1, 2, 3, 4$
7	NorESM2-LM	rxi1p1f1, where $x = 1, 2, 3$
8	GISS-E2-1-G	rxi1p1f1, where $x = 1, 2, 3, 4, 5$
9	IPSL-CM6A-LR	rxi1p1f1, where $x = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10$

Table S1. CMIP6 models used in this study. For all models, the *hist-nat*, *hist-GHG*, *aer*, *piControl* and *historical* experiments were analysed.

Text S2.

The 'residual' term in figure 3c and f of the main text does not allow us to parse between the different ocean processes that may be contributing to the ocean heat content tendency due to mixing. In order to investigate whether the true mixing corresponds to the residual

curves in figure 3, we analyse a single climate model - ACCESS-CM2 - which archives detailed tendency budget terms. We assess the time window between 1995 and 2014 where decelerating cooling due to aerosols is evident. The ocean heat content tendency due to mixing is represented by numerical mixing, neutral diffusion, vertical mixing and miscellaneous mixing processes (Holmes et al., 2019). The surface forcing tendency is composed of surface radiative fluxes, surface volume fluxes (i.e. change in the heat flux due to changing volume), and penetrative shortwave heating.

In the GHG-only ACCESS-CM2 runs, there is a reduction in shortwave penetration in the layers $\overline{\Theta^p} > 20^\circ$ C (see figure S1a). This reduction is largely counteracted by volume fluxes in the precipitative tropics, with the opposite effect in the evaporative sub-tropics. The dipole around the sub-tropical gyres is driven primarily by the surface heat flux, aligning with the results in figure 3b. In the AA-only ACCESS-CM2 runs, the opposite effect is seen in the surface heat flux diagnostics (see figure S1c). Shortwave penetration warms the surface tropics and sub-tropics, and surface volume fluxes counteract this effect in the tropics. As in the GHG-only runs, surface heat fluxes are primarily responsible for the dipole in the sub-tropics.

The mixing tendency profiles in figure S1b and d show that numerical and vertical mixing are the dominant factors modulating ocean heat content in the tropics and sub-tropics ($\overline{\Theta^p} > 10^\circ$ C). In the sub-polar and polar regions, which represent the high latitudes and deep ocean, vertical mixing and neutral diffusion are dominant processes maintaining ocean cooling due to aerosols. In the GHG-only simulations, the coldest temperature percentiles ($\overline{\Theta^p} < 10^\circ$ C) still exhibit significant numerical mixing, while in the AA-only

simulations numerical mixing is relatively small. Thus, in the AA-only runs, eddies and convection are most likely driving continued deep ocean cooling despite the stabilisation of effective radiative forcing and mean surface air temperatures.

References

Holmes, R. M., Zika, J. D., & England, M. H. (2019). Diathermal Heat Transport in a Global Ocean Model. *Journal of Physical Oceanography*, *49*(1), 141–161. doi: 10.1175/jpo-d-18-0098.1

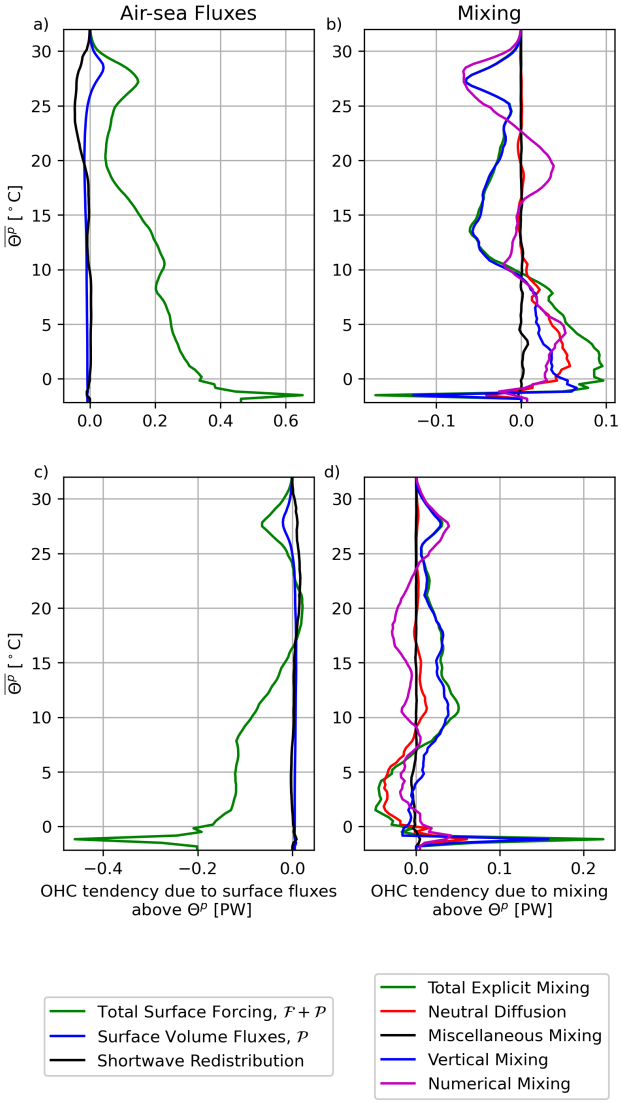

Figure S1. A decomposition of mixing and surface flux terms in the ACCESS-CM2 suite of DAMIP simulations. a and b: Surface fluxes and mixing terms in the GHG-only simulation and c - d: Surface fluxes and mixing terms in the AA-only simulation. Diagnostics are calculated for the 1995-2014 time window.