

**Ocean heat uptake and interbasin redistribution driven by anthropogenic aerosols and
greenhouse gases**

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Abstract

Anthropogenic aerosols and greenhouse gases have played important roles in modulating the storage and distribution of heat in oceans since the industrial age. Here we isolate and quantify the effects of both using coupled climate model simulations. We show that, relative to the pre-industrial ocean, the Southern Ocean imports heat from the Indo-Pacific Ocean but exports heat into the Atlantic Ocean in response to anthropogenic aerosols. Ocean heat uptake diminishes in the subpolar Atlantic. Alterations in ocean circulation and temperature have a weak compensation in contributing to interbasin heat exchange. Consequently, interbasin heat exchange contributes comparably to ocean heat uptake changes to modifying the stored heat in the Atlantic and Indo-Pacific. The greenhouse-gas-associated changes are the opposite of the aerosol-associated changes. Anthropogenic greenhouse gases promote the ocean heat uptake in the subpolar Atlantic and allow the Southern Ocean to import heat from the Atlantic but export heat to the Indo-Pacific. The cause of this ocean heat redistribution is distinct from the aerosol-forcing scenario, seeing that ocean circulation effects are strongly offset by temperature shifts. Accordingly, interbasin heat exchange is much less important than ocean heat uptake changes for greenhouse gas-associated ocean heat storage. Our results suggest that the aerosol-driven changes in ocean circulations and associated interbasin heat transports are more effective in altering oceanic heat distribution than those driven by globally increasing greenhouse gases.

Main

Anthropogenic aerosols and greenhouse gases are regarded as the two major climate forcing agents driving Earth's energy imbalance since the industrial age^{1,2}. Most of the excessive energy has been absorbed by oceans through surface in the form of ocean heat uptake (OHU), as

reflected from the changes in the net surface heat flux. On multi-decadal or longer time scales, compared to the North Atlantic, the Southern Ocean has experienced larger OHU during the historical period^{3,4}, especially since the middle of the twentieth century⁵, which at least can be attributed in part to the distinct anthropogenic aerosol and greenhouse gas impacts. It has been suggested that the rising greenhouse gases enhance the OHU over most of global oceans, whilst in the North Atlantic, greenhouse gas-induced OHU increases are heavily compensated by aerosol-induced OHU decreases, thus leaving marginal ocean heat content (OHC) changes in this ocean basin⁶⁻¹⁰. Over the recent decade, internal climate variability seems also to influence the regional OHU. The rapid and high heat gain of the Southern Ocean during 2005-2015 was indicated to result from a combined effect of anthropogenic warming and internal variability¹¹. In the North Atlantic, a reversal of warming trend was found over 2005-2014 when compared to the previous decade, which could be related to a long-term freshening in the deep Labrador Sea¹².

Nevertheless, the heat taken by oceans in response to anthropogenic aerosols and greenhouse gases is not always stored locally, seeing that the concurrent ocean circulation changes modify ocean heat transports (OHTs) across individual basins as well as interbasin heat exchange. For example, the increase of anthropogenic greenhouse gas causes a weakened Atlantic meridional overturning circulation (AMOC), and hence alters the meridional OHT in the Atlantic¹³⁻¹⁵ and the interbasin heat exchange between the Atlantic and Southern Oceans¹⁶⁻¹⁸. Meanwhile, an anomalous clockwise ocean circulation is generated in the Indo-Pacific through a geostrophic response to the AMOC slowdown¹⁷⁻²⁰, which largely accounts for the OHT change across the boundary between the Indo-Pacific and Southern Oceans^{17,19,20}.

Unlike greenhouse gases, the impacts of aerosols on global OHU, redistribution and storage have received less attention, and thus their patterns and the working physical processes

remain unclear. Here we exploit historical aerosol and greenhouse gas single-forcing experiments²¹ with Coupled Model Intercomparison Projects Phase 5/6 (CMIP5/6) models to isolate and quantify the impacts of anthropogenic aerosols and greenhouse gases on global ocean heat uptake, redistribution and storage and explore the underlying physical mechanism under either driver.

Aerosol and greenhouse gas driven oceanic heat changes

We examine the OHU changes over 1861-2005 relative to the preindustrial time in the aerosol-only and greenhouse-gas-only simulations with a 9-model ensemble of CMIP5/6 models (Methods). The multi-model mean shows that the increasing emissions and concentrations of anthropogenic aerosols between 1861 and 2005 lead to an OHU decrease in the North Atlantic subpolar region (Fig. 1a). Compared to aerosol effects, anthropogenic greenhouse gas increases generally have an opposite effect on OHU during this period. In the subpolar North Atlantic, the greenhouse gas-induced OHU increase acts to offset the aerosol-induced OHU decrease (Fig. 1b).

Meanwhile, we look into the trend of the vertically integrated ocean heat content (OHC) over 1861-2005, or equivalently, the ocean heat storage (OHS). We find a different pattern of OHS from OHU. Anthropogenic aerosols drive reduced OHS over global oceans except for a few sites such as the subpolar North Atlantic where OHU decreases but OHS increases (Fig. 1c) primarily owing to a strengthened AMOC and associated heat transport there⁸. Similarly, the rising anthropogenic greenhouse gases lead to enhanced OHS over most of global oceans but reduced OHS in the subpolar North Atlantic despite OHU increases there (Fig. 1d), which is related to a weakened AMOC¹⁴. Under either anthropogenic aerosol or greenhouse gas forcing,

the contrary changes between OHU and OHS in the subpolar North Atlantic manifest the turbulent heat flux feedback^{10,14,22,23} or North Atlantic redistribution feedback²⁴ via the North Atlantic cooling (for aerosols)/warming (for greenhouse gases) hole (Extended data Fig. 1a,b), and implies heat redistribution by ocean circulation change. Anthropogenic aerosol (greenhouse gas) forcing perturbs the climate system and initializes the feedback that involves an AMOC strengthening (weakening), a meridional convergence (divergence) of oceanic heat transport and diminished (enhanced) OHU in the subpolar North Atlantic^{8,14}.

To elaborate on the anthropogenic aerosol and greenhouse gas effects on ocean heat redistribution, we conduct a heat budget analysis that links OHU, meridional OHT and OHS^{14,25} (Methods). We find that anthropogenic aerosols bring about an anomalous oceanic heat convergence [$-\partial(OHT)/\partial y > 0$] over 31°N-70°N and divergence [$-\partial(OHT)/\partial y < 0$] in the rest of the Atlantic (Fig. 2a). The former heat convergence acts to warm the subpolar North Atlantic, which overweighs the cooling due to an anomalous heat loss via ocean surface and hence allows for heat stored in the subpolar North Atlantic. The latter heat divergence primarily accounts for the abated heat storage in the rest of the Atlantic. On the contrary, anthropogenic greenhouse gases induce an anomalous oceanic heat divergence to the north of 32°N and convergence to the south (Fig. 2b). The former heat divergence overweighs the surface heat uptake in the subpolar North Atlantic and results in diminished heat storage there. The latter heat convergence explains the mounting heat stored in the rest of the Atlantic. It merits attention that aerosol-induced changes in OHU and $-\partial(OHT)/\partial y$ are about twice the magnitude of those induced by greenhouse gases over the subpolar North Atlantic. This is possibly because a majority of the models in the heat budget analysis here (Methods) come from the CMIP6 in which aerosols

impose a stronger impact on ocean circulations such as the AMOC than greenhouse gases during the historical period²⁶.

Oceanic heat redistribution due to anthropogenic aerosols and greenhouse gases is not limited to the Atlantic but also extends to other ocean basins via inter-basin heat exchanges. We probe the OHT change across the boundary between the Atlantic and Southern Oceans. Especially, driven by anthropogenic aerosols, changes in ocean circulations such as the AMOC strengthening (Fig. 3a) cause an increase of the northward OHT across the boundary between Atlantic and Southern Oceans (30°S) by 29.83 ± 19.01 TW (1TW = 10^{12} Watt) (Fig. 4a). This circulation-induced OHT increase is slightly compensated by a temperature-induced OHT decrease (Methods) primarily due to the cooling in surface waters (Fig. 3a), leading to a net anomalous northward OHT of 22.56 ± 19.11 TW (Fig. 4a). On the other hand, under the rising greenhouse gases, ocean circulation changes such as the AMOC weakening (Fig. 3b) reduce the northward OHT by 5.69 ± 14.01 TW, which is almost completely compensated by a temperature-induced OHT increase mainly owing to the warming in surface waters (Fig. 3b), and results in a very small net anomalous southward OHT of 0.06 ± 11.31 TW (Fig. 4b). This anomalous OHT is much smaller in magnitude than its counterpart due to anthropogenic aerosols, and meanwhile, exhibits large uncertainty.

Inter-basin heat exchanges also occur between the Indo-Pacific and Southern Oceans. As a part of global adjustment of ocean thermocline^{18,27} in response to anthropogenic aerosol forcing, an anomalous anticlockwise ocean circulation is generated in the Indo-Pacific basin^{28,29} (Fig. 3c). This anomalous ocean circulation produces a southward OHT across the boundary between the Indo-Pacific and Southern Oceans (Fig. 4c). Since the ocean circulation-driven OHT component is only slightly compensated by a temperature-driven OHT component, a large

amount of anomalous ocean heat is exported from the Indo-Pacific to the Southern Ocean. On the other hand, in response to anthropogenic greenhouse gases, an anomalous clockwise ocean circulation is formed over the Indo-Pacific (Fig. 3d), which generates an anomalous northward OHT across the boundary between the Indo-Pacific and Southern Oceans. A majority of this ocean circulation-induced OHT anomaly is offset by a temperature-induced southward OHT anomaly. Therefore, anomalous oceanic heat is transported from the Southern Ocean to the Indo-Pacific but with magnitude much smaller than that under the aerosol-driven scenario (Fig. 4d).

We delve into the change in oceanic heat over the Southern Ocean that connects both Atlantic and Indo-Pacific Oceans. Relative to the preindustrial time, anthropogenic aerosols bring on a dipole-like change in OHU (Fig. 2e) in which the ocean releases heat (presenting negative net surface heat flux anomalies) to the south of 45°S but takes heat (presenting positive net surface heat flux anomalies) to the north between 1861 and 2005. Most of the taken heat is further redistributed by ocean circulations in the form of anomalous OHT convergence in 46°S-63°S and anomalous OHT divergence to the north of 46°S. As a result, OHS shows negative anomalies almost over the Southern Ocean with slight positive anomalies between 49°S and 51°S. Consistent with the OHS changes, we find that aerosol changes induce a wide-spreading cooling in the Southern Ocean peaking at -0.03 K/decade (Fig. 3e). Such Southern Ocean cooling may be attributed to the aerosol forcing located in the tropical regions, dominated by East/South Asia³⁰. Note here, the heat redistribution or OHT anomalies could be achieved either via the climatological meridional overturning circulation (MOC) carrying ocean temperature anomalies or via MOC anomalies acting on the climatological ocean temperature^{4,11,15,17,25,31-33}. Particularly, anthropogenic aerosols drive an equatorward-weakened residual MOC in the Southern Ocean (Fig. 3e). This is because Southern Hemisphere westerly winds displace

equatorward and become weaker in response to anthropogenic aerosols^{34,35} (Extended Data Fig. 2a). The wind-driven Deacon cell accordingly becomes equatorward weakened and is partially compensated by the changes in the eddy-induced MOC (Methods), which leads to an equatorward-weakened residual MOC in the Southern Ocean (Extended Data Fig. 3a,c,e).

In contrast to aerosols, anthropogenic greenhouse gases engender poleward intensified Southern Hemisphere westerly winds³⁶ (Extended Data Fig. 2b) and hence a poleward intensified wind-driven Deacon Cell. The latter is partially compensated by eddy-induced MOC between 45°S-53°S, resulting in a poleward shifted and strengthened residual MOC (Extended Data Fig. 3b,d,f). Relative to the preindustrial time, anthropogenic greenhouse gases generally promote Southern Ocean OHU in a peak at 55°S (Fig. 2f). Meanwhile, OHT diverges in 49°S-69°S and converges in 36°S-48°S. With combined effects of OHU and heat redistribution, OHS exhibits positive anomalies over the Southern Ocean peaking at 43°S. The greenhouse gases induced positive OHS anomalies manifest a subsurface warming in the Southern Ocean with a marked downward warming tongue between 35°S and 55°S (Fig. 3f). It merits attention that other external forcings, such as stratospheric ozone depletion and tropospheric ozone increases, can also drive the interior Southern Ocean warming during the twentieth century³⁷⁻³⁹.

Basin-integrated ocean heat budget alterations

We further explore the changes in the basin-integrated ocean heat budget during 1861-2005 relative to the preindustrial time. Driven by anthropogenic aerosols, the Atlantic receives heat from both the Southern and Arctic Oceans at rates of 22.56 ± 19.11 TW and 3.08 ± 24.83 TW, and meanwhile, loses heat at a rate of 36.77 ± 24.26 TW via ocean surface, which leads to reduced heat storage at a rate of 11.13 ± 16.30 TW (Fig. 5a). On the other hand, driven by anthropogenic

greenhouse gas forcing, the Atlantic imports heat at rates of 2.08 ± 10.83 TW from the Arctic but exports heat at a rate of 0.06 ± 11.31 TW to the Southern Ocean, and takes heat at a rate of 31.48 ± 11.94 TW from the atmosphere, which results in an increase of heat storage at a rate of 33.50 ± 7.20 TW (Fig. 5b).

For the Indo-Pacific Oceans, they import heat at a rate of 1.47 ± 2.15 TW from the Arctic Ocean but export heat at a rate of 25.05 ± 20.40 TW to the Southern Ocean under anthropogenic aerosol forcing. Meanwhile, the oceans lose heat at a rate of 20.61 ± 15.35 TW via ocean surface and hence have a decline of heat storage at a rate of 44.19 ± 18.49 TW (Fig. 5a). By contrast, the Indo-Pacific Oceans export heat at a rate of 1.09 ± 1.11 TW to the Arctic but import heat at a rate of 10.50 ± 7.96 TW from the Southern Ocean under anthropogenic greenhouse gas forcing. The integrated OHU over the basins amounts to 36.04 ± 10.60 TW, and an increase of heat storage at a rate of 45.45 ± 9.60 TW ensues (Fig. 5b).

Driven by anthropogenic aerosols, the Southern Ocean loses heat at a rate of 16.45 ± 16.29 TW via ocean surface. It also has a net heat import of 2.49 ± 11.62 TW from the north and a heat export of 0.19 ± 2.71 TW to the marginal seas around Antarctica such that the stored heat within the basin diminishes at a rate of 14.15 ± 15.63 TW (Fig. 5a). While driven by anthropogenic greenhouse gases, the Southern Ocean takes heat at a rate of 62.08 ± 17.29 TW from the atmosphere, exports heat of 10.44 ± 13.35 TW to the north and imports heat at a rate of 0.33 ± 4.40 TW from the marginal seas in the south. As a result, the basin has an increase of the stored heat at a rate of 51.98 ± 17.31 TW (Fig. 5b).

Observational constraints on simulated ocean heat changes

Compared to CMIP5 models, CMIP6 models have been suggested to produce a stronger aerosol cooling⁴⁰⁻⁴² and a resultant stronger increase in AMOC strength during the historical period^{26,43}. Also, CMIP6 models include more sophisticated aerosol indirect effects on cloud microphysics⁴⁴, which modulate the cloud forcing and potentially relate to a much higher climate sensitivity in these models^{45,46}. Recently, the systematic CMIP6 model biases in surface ocean heat uptake have been isolated via a tracer-percentile framework as compared to observations⁴⁷. In this context, to assess the creditability of CMIP5 and CMIP6 models in simulating oceanic heat changes (Extended Data Fig. 4-6), we resort to observed OHC changes for constraints on model results.

We examine the upper 2000-m OHC changes relative to the 1960-1969 average from 6 observational datasets and from historical simulations with 11 CMIP5 models and 11 CMIP6 models (Extended Data Table 1, Methods) over individual oceans between 1960 and 2005 (Fig. 6). In the Atlantic, the observed, CMIP5 and CMIP6 model OHC trends are 0.98 ± 0.57 ZJ/year, 1.04 ± 0.56 ZJ/year and 0.48 ± 0.69 ZJ/year ($1 \text{ ZJ} = 10^{21}$ Joule), indicative of the CMIP5 models simulating an oceanic heat increase closer to the observations within this basin (Fig. 6b). On the other hand, the observed, CMIP5 and CMIP6 model OHC trends are 0.54 ± 0.85 ZJ/year, 1.39 ± 1.04 ZJ/year and 0.22 ± 0.66 ZJ/year in the Indo-Pacific where the observed trend is between the simulated by CMIP5 and CMIP6 models (Fig. 6d). Over the Southern Ocean, the observed, CMIP5 and CMIP6 model OHC trends are 1.28 ± 0.36 ZJ/year, 1.81 ± 0.79 ZJ/year and 1.12 ± 0.55 ZJ/year, meaning that the CMIP6 models simulate an oceanic heat increase closer to the observations in this basin (Fig. 6f). Overall, albeit more of the CMIP6 models include the more sophisticated aerosol indirect effects than the CMIP5 models, they do not necessarily have a better performance than the CMIP5 models in simulating historical ocean heat uptake and

storage. We can see CMIP6 models generally exhibit a stronger aerosol cooling effect than CMIP5 models in terms of OHC trends in all three basins (Fig. 6b,d,f), but there is no statistically significant difference in oceanic heat changes between observations and CMIP5/6 models (Methods). This result suggests that our estimate of oceanic warming from both CMIP5 and CMIP6 model simulations are plausible and under the constraint of observations when considering observation uncertainties.

To summarize, we find that anthropogenic aerosols and greenhouse gases have caused heat uptake, redistribution and storage over global oceans via different mechanisms between 1861 and 2005. Driven by anthropogenic aerosols, the Southern Ocean imports heat from the Indo-Pacific but exports heat into the Atlantic, accompanying with reduced OHU in the subpolar Atlantic. Alterations in ocean circulation and ocean temperature have a weak compensation in contributing to interbasin OHT changes. As a result, interbasin OHT changes are comparable to basin-integration OHU changes for the Atlantic and Indo-Pacific Oceans, meaning that both factors play important roles in altering OHS in these ocean basins. Nevertheless, when driven by anthropogenic greenhouse gases, excessive atmospheric heat enters the subpolar Atlantic while the Southern Ocean imports heat from the Atlantic but exports heat into the Indo-Pacific. Compared to aerosol forcing, alterations in ocean circulation and ocean temperature have a much stronger compensation between their contributions to interbasin OHT changes. Thereby, under the rising anthropogenic greenhouse gases, interbasin OHT changes are far smaller than basin-integration OHU changes such that the latter dominate the OHS changes over individual basins.

One may also note the evolution of the roles of anthropogenic aerosols and greenhouse gases in modulating global ocean heat uptake and storage in future climate. For example, following one possible shared socio-economic pathway (SSP245), anthropogenic greenhouse

gases could impose much stronger impacts than aerosols on OHU and OHC trends over 2021-2100 (Extended Data Fig. 7 and Table 2). Given the distinct trajectories of anthropogenic aerosols and greenhouse gases in various SSPs, the impacts of both drivers on global ocean heat uptake and storage, could vary from historical to future climate, or between different SSP scenarios.

Author Contributions Statement

S.L. performed the analysis and wrote the original draft of the manuscript. W.L. conceived the study and conducted the simulations with CESM1-CN. All authors contributed to interpreting the results and made substantial improvements to the manuscript.

Competing Interests Statement

The authors declare no competing interests.

Figure Legends

Fig. 1: Anthropogenic aerosol and greenhouse gas driven changes in ocean heat uptake and ocean heat content trend. (a,b) Annual mean changes (relative to the preindustrial time) in global ocean heat uptake (OHU) during 1861-2005 (shading) for the multi-model means of the 9-model ensemble **(a)** historical anthropogenic aerosol-only (HIST-AER) and **(b)** historical anthropogenic greenhouse gas-only (HIST-GHG) simulations. **(c,d)** As in (a,b) for the changes in the full-depth integrated annual mean ocean heat content (OHC) trend during 1861-2005. The stipples refer to the regions where at least 6 of the 9 models agree with the sign of the multi-

model mean OHU or OHC trend change. The base-map is from NCAR Command Language map outline databases.

Fig. 2: Anthropogenic aerosol and greenhouse gas driven changes in oceanic heat budgets for individual basins. (a,c,e) Annual mean changes (relative to the preindustrial time) in the zonally integrated full-depth oceanic heat budget over 1861-2005: ocean heat uptake (OHU; multi-model mean, MMM, blue; inter-model spread, light blue), $-\partial(\text{OHT})/\partial y$ (MMM, red; inter-model spread, light red) where OHT means ocean heat transport, and ocean heat storage (OHS; MMM, black; inter-model spread, gray) in the (a) Atlantic, (c) Indo-Pacific and (e) Southern Oceans for the 9-model ensemble historical anthropogenic aerosol-only (HIST-AER) simulation. Inter-model spread is denoted by one standard derivation (SD). (b,d,f) are as in (a,c,e) but for the 9-model ensemble historical anthropogenic greenhouse gas-only (HIST-GHG) simulation.

Fig. 3: Anthropogenic aerosol and greenhouse gas driven ocean temperature and meridional overturning circulation changes over individual basins. (a,c,e) Changes (relative to the preindustrial time) in the annual and zonal mean temperature trend over 1861-2005 (color shading in 10^{-2} K/decade) in the (a) Atlantic, (c) Indo-Pacific and (e) Southern Oceans for the multi-model mean of the 9-model ensemble historical anthropogenic aerosol-only (HIST-AER) simulation. Changes in the annual mean Eulerian mean plus eddy-induced meridional overturning circulation (MOC) is overlapped for each basin [contours with an interval of 0.2 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$), zero contours thickened, solid positive and dashed negative]. (b,d,f) As in (a,c,e) but for the 9-model ensemble historical anthropogenic greenhouse gas-only (HIST-GHG)

simulation. The stipples refer to the regions where at least 6 of the 9 models agree with the sign of the multi-model mean ocean temperature trend change.

Fig. 4: Decompositions of anthropogenic aerosol and greenhouse gas driven interbasin heat exchanges. (a,c) Annual mean changes (relative to the preindustrial time) in the meridional ocean heat transport (ΔOHT), the components due to ocean circulation alteration ($\Delta \overline{OHT}_{\text{cl}}$) and ocean temperature alteration ($\Delta \overline{OHT}_{\text{t}}$) and the residual term (Res) due to the effects of eddies, diffusion and the nonlinearity resulting from ocean circulation and temperature changes across the boundaries (a) between the Atlantic and the Southern Oceans and (c) between the Indo-Pacific and the Southern Oceans during 1861-2005 from the 9-model ensemble historical anthropogenic aerosol-only (HIST-AER) simulation. (b,d) As in (a,c) but for the 9-model ensemble historical anthropogenic greenhouse gas-only (HIST-GHG) simulation. Results are illustrated—as explained by the example on the top right of each panel—in form of multi-model mean (MMM, dot) $\pm$ one standard deviation (SD) among models (bars) as well as for each model (colored cross). Positive (negative) values indicate anomalous northward (southward) ocean heat transport.

Fig. 5: Anthropogenic aerosol and greenhouse gas driven changes in basin integrated oceanic heat budgets. Ocean basins defined in the current study for the basin integration: the Atlantic Ocean (green), the Southern Ocean (blue) and the Indo-Pacific Oceans (pink). Annual mean changes (relative to the preindustrial time) during 1861-2005 in the basin integrated full-depth oceanic heat budget for each basin that includes basin-integrated ocean heat uptake (OHU, red, $\otimes$ denoting downward OHU anomalies, $\odot$ denoting upward OHU anomalies), basin

integrated ocean heat storage (OHS, black, positive denoting an OHS increase and negative denoting an OHS decrease) and interbasin ocean heat transport (blue arrow, southward negative and northward positive) for the 9-model ensemble **(a)** historical anthropogenic aerosol-only (HIST-AER) and **(b)** historical anthropogenic greenhouse gas-only (HIST-GHG) simulations. The numbers are presented in form of multi-model mean $\pm$ one standard deviation among models, are in units of TW ($1\text{TW} = 10^{12}$ Watt). The base-map is from NCAR Command Language map outline databases.

Fig. 6: Observed and simulated ocean heat content changes. **(a,c,e)** Annual mean upper 2000-m ocean heat content (OHC) anomalies (relative the 1960-1969 average) integrated over the **(a)** Atlantic, **(c)** Indo-Pacific and **(e)** Southern Oceans during 1960-2005 from 6 observational datasets (mean, green; uncertainty, light green; $1\text{ ZJ} = 10^{21}$ Joule) and historical simulations (HIST) with 11 CMIP5 models (multi-model mean, MMM, red; inter-model spread, light red) and 11 CMIP6 models (MMM, blue; inter-model spread, light blue). Inter-model spread is denoted by one standard derivation (SD). **(b,d,f)** Trends of annual mean upper 2000-m OHC integrated over the **(b)** Atlantic, **(d)** Indo-Pacific and **(f)** Southern Oceans during 1960-2005 for observational datasets (Obs), CMIP6 HIST [H(6)], CMIP6 HIST-AER[A(6)], CMIP6 HIST-GHG [G(6)], CMIP5 HIST [H(5)], CMIP5 HIST-AER [A(5)] and CMIP5 HIST-GHG [G(5)] simulations—as exemplified on the bottom left—in form of observation/model mean (Mean, dot) $\pm$ one SD among observations/models (bars). Ocean temperature drifts (500-year temperature trends in preindustrial control runs, see Methods) have been removed from CMIP5/6 model simulations before the calculation of OHC.

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Methods

CMIP5 and CMIP6 model simulations

We adopt 11 CMIP5 models and 11 CMIP6 models (Extended Data Table 1) that are forced only by historical anthropogenic aerosol (HIST-AER) or greenhouse gas (HIST-GHG) changes. The aerosol-only experiments with 10 CMIP5 models were identified as “historicalMisc” in the CMIP5. Here, we name them “HIST-AER” for the consistence with CMIP6 aerosol-only experiments. The other CMIP5 model is CESM1-CN, in the version of T31_gx3v7¹⁹. We force this model following the CMIP5 protocol to generate the HIST-AER and HIST-GHG simulations and produce three ensemble members for either simulation. Also, we employ the pre-industrial control and historical simulations with the 22 CMIP5/6 models (Extended Data Table 1). For each model, we probe the last 500-year output of the pre-industrial control (piControl) simulation and the ensemble mean of the historical simulation (HIST) over 1861-2005, a period during which data are available from all the models. Based on the ensemble means of these models, we also compute the multi-model mean and inter-model spread (one standard deviation). Besides, we construct a 9-model ensemble from the 22 CMIP5/6 models, since all the variables needed for the ocean heat budget analysis are available in these 9 models (CanESM5, CESM1-CN, CNRM-CM6-1, CSIRO-Mk3-6-0, GISS-E2-1-G, HadGEM3-GC31-LL, IPSL-CM6A-LR, NorESM1-M and NorESM2-LM, see Extended Data Table 1).

The CMIP5/6 HIST-AER and HIST-GHG simulations display generally consistent patterns of OHU, OHS and North Atlantic cooling (warming) hole while also indicate some detailed differences (Extended Data Figs. 4-6). For example, compared to the CMIP5 models, the CMIP6 models simulate a larger reduction of OHU in the subpolar North Atlantic when driven by anthropogenic aerosols, and enhanced OHU in a more eastward location in the

subpolar North Atlantic when driven by anthropogenic greenhouse gases (Extended Data Fig. 4). Zonally integrated OHU changes reveal that the CMIP6 models simulate a much larger aerosol-driven OHU decrease in the Northern Hemisphere oceans than the CMIP5 models (Extended Data Fig. 5), which is consistent with the stronger aerosol cooling in the former models. When we compare the zonally integrated aerosol- and greenhouse gas-driven OHU changes, we discover that aerosol-driven OHU decrease overweighs greenhouse gas-driven OHU increase between 40°N and 60°N during 1861-2005 in the CMIP6 models, which leads to an OHU decrease seen from the sum of the two OHU changes (Extended Data Fig. 5). The opposite is true for the CMIP5 models (Extended Data Fig. 5).

Additionally, we employ the SSP245 simulation and accompanying aerosol-only (SSP245-AER) and greenhouse-gas-only (SSP245-GHG) single forcing experiments with four CMIP6 models (CanESM5, GISS-E2-1-G, MIROC6 and NorESM2-LM, see Extended Data Table 2) spanning from 2021 to 2100. We examine the multi-model mean changes in these simulations relative to the preindustrial state.

Observational ocean temperature datasets

To evaluate the creditability of the CMIP5 and CMIP6 models in simulating historical oceanic heat changes, we construct a 6-member ensemble of observational datasets by including four objectively analyzed ocean datasets: the DePreSys ocean temperature analysis⁴⁸, the EN4 (version 4.2.2) ocean temperature analysis⁴⁹, the Institute of Atmospheric Physics (IAP) ocean temperature analysis⁵⁰ and the subsurface temperature analysis led by Ishii (version 7.3.1)⁵¹, and two ocean reanalysis products, the German contribution to the Estimating the Circulation and Climate of the Ocean project version 3 (GECCO3) ocean synthesis⁵² and the Ocean Reanalysis

System 4 (ORAS4)⁵³ from European Centre for Medium-Range Weather Forecasts. The DePreSys ocean temperature analysis has a horizontal resolution of 1.25° with 20 vertical levels on a full-depth ocean and spans from 1950 to 2006. The EN4 ocean temperature analysis has a horizontal resolution of 1° with 42 vertical levels on a full-depth ocean and spans from 1900 to the present. There are four versions of EN4 data available: Gouretski and Reseghetti (2010) XBT corrections and Gouretski and Cheng (2020) MBT corrections, Levitus et al. (2009) corrections, Cowley et al. (2013) XBT corrections and Levitus et al. (2009) MBT corrections, and Cheng et al. (2014) XBT corrections and Gouretski and Cheng (2020) MBT corrections. We use the average of the four versions to represent the EN4 data. The IAP ocean temperature analysis has a horizontal resolution of 1° with 41 vertical levels from surface down to 2000 m and spans from 1940 to the present. The subsurface temperature analysis led by Ishii has a horizontal resolution of 1° with 28 vertical levels from surface down to 3000 m and spans from 1955 to the present. The GECCO3 is based on the Massachusetts Institute of Technology general circulation model, which has a nominally 0.4° resolution horizontal resolution and 40 vertical levels on a full-depth ocean and spans from 1948 to 2018. The ORAS4 has a global ocean coverage of 1° horizontal resolution with 42 vertical levels on a full-depth ocean and spans from 1958 to 2017. We focus on the OHC during the period of 1960-2005 when data are available from all the observational datasets as well as the CMIP5/6 model historical simulations. We calculate the ensemble mean of the observational datasets and estimate the observation uncertainty using one standard deviation among the observational datasets.

Significance of observation and model simulation results

We conduct Student's t-test for the upper 2000-m OHC trends during 1960-2005 in the Atlantic, Indo-Pacific and Southern Oceans to determine if there is a statistically significant difference between the means of the two groups: 6 observation datasets and 11 CMIP5 models, or 6 observation datasets and 11 CMIP6 models. We find the p-value is larger than 0.05 in any of the above tests, which indicates that there is no statistically significant difference in oceanic heat changes between observations and CMIP5/6 models at the 95% confidence interval.

Ocean heat budget analysis

We analyze the ocean heat budget in each ocean basin that links ocean heat uptake, transport and storage^{14,19,25}. The zonally integrated full-depth oceanic heat budget at certain latitude is

$$\int_{X_1}^{X_2} \int_{-H}^0 \rho_l C_l \frac{d\theta}{dt} dz dx + \int_{X_1}^{X_2} \int_{-H}^0 \rho_l C_l [\nabla \cdot (\mathbf{v}\theta + D)] dz dx = \int_{X_1}^{X_2} (SHF) dx \quad (1)$$

where X_1 and X_2 denote the longitudes of the western and eastern boundaries of the basin at certain latitude, ρ_l is seawater density, C_l is the specific heat of sea water, θ is potential temperature of sea water, $-H$ denotes the depth of ocean bottom. SHF denotes the net surface heat flux. ∇ and $\mathbf{v}$ are three-dimensional gradient operator and velocity. $\mathbf{v} = \bar{\mathbf{v}} + \mathbf{v}^*$ where $\bar{\mathbf{v}}$ denotes Eulerian-mean velocity and $\mathbf{v}^*$ denotes the sum of meso- and sub-mesoscale eddy-induced velocities. D denotes diffusion and other sub-grid processes.

Based on Eq. (1), we define ocean heat content as

$$OHC = \int_{X_1}^{X_2} \int_{-H}^0 \rho_l C_l \theta dz dx \quad (2)$$

and OHC tendency as ocean heat storage, i.e.,

$$OHS = \frac{1}{L} OHC = \frac{1}{L} \int_{-L}^L \int_{-L}^L \rho_1 C_1 \theta dz dx \quad (3)$$

and ocean heat uptake as

$$OHU = \int_{-L}^L (SHF) dx \quad (4)$$

and meridional ocean heat transport as

$$OHT = \int_{-L}^L \int_{-L}^L \rho_1 C_1 (\bar{v}\theta + v^*\theta + D) dz dx \quad (5)$$

which shows that meridional ocean heat transports can be induced by Eulerian-mean flow, eddies and diffusion.

Therefore, the heat budget by Eq. (1) can be written as

$$OHS = OHU - \frac{1}{L} OHT \quad (6)$$

which indicates that ocean heat storage is determined by heat uptake from atmosphere-ocean interface and heat redistribution in form of the meridional gradient of ocean heat transport. Here, $-\frac{1}{L} OHT$ could be related to changes in ocean circulations—such as the AMOC—and resultant meridional convergence or divergence of oceanic heat transport.

Accordingly, the basin integrated full-depth oceanic heat budget is

$$[OHS] = [OHU] - (OHT_N - OHT_S) \quad (7)$$

where $[.]$ denotes a basin integration, OHT_N and OHT_S denote the ocean heat transports across the northern and southern boundaries of the basin.

Relative to the preindustrial time, the anthropogenic aerosol- or greenhouse gas-driven changes in the zonally integrated full-depth oceanic heat budget at certain latitude during 1861-2005 are defined as:

$$\Delta OHS = \Delta OHU - \Delta \left(\frac{1}{L} OHT \right) \quad (8)$$

where Δ refers to the differences between the HIST-AER/HIST-GHG experiment and the preindustrial control run. ΔOHS can be represented by the change in the OHC trend $[\Delta Tr(OHC)]$ that is defined as

$$\Delta Tr(OHC) = Tr(OHC) - Tr(OHC_{preind}) \quad (9)$$

where $Tr(OHC)$ and $Tr(OHC_{preind})$ denote the OHC trends in the HIST-AER/HIST-GHG simulation and preindustrial control run with CMIP5/6 models. $Tr(OHC_{preind})$ may reflect a temperature drift in the preindustrial control run, which is not necessarily zero^{54,55} and can persist in the HIST-AER and HIST-GHG simulations. The difference between $Tr(OHC)$ and $Tr(OHC_{preind})$ facilitates a cancellation of the drifts between the HIST-AER/HIST-GHG simulation and preindustrial control run and hence a reduction of the effect of drifts on the OHC trend in the HIST-AER/HIST-GHG simulation.

Similarly, the anthropogenic aerosol- or greenhouse gas-driven changes in the basin integrated full-depth oceanic heat budget can be written as

$$\Delta[OHS] = \Delta[OHU] - (\Delta OHT_1 - \Delta OHT_0) \quad (10)$$

We further decompose the Eulerian mean OHT change into the component that is driven by ocean circulation anomaly ($\overline{OHT}_1$) and the component that is driven by ocean temperature anomaly ($\overline{OHT}_0$), such as

$$\overline{OHT}_1 = \iint \rho_1 C_1 \mathbf{v}' \cdot \bar{\theta}_1 \mathbf{e}_z dx dy \quad (11)$$

where $\mathbf{v}'$ denotes the change in monthly Eulerian-mean velocity and $\bar{\theta}_1$ denotes the monthly climatological ocean temperature in the preindustrial control run.

$$\overline{OHT}_0 = \iint \rho_1 C_1 \bar{\mathbf{v}}_1 \cdot \theta^1 \mathbf{e}_z dx dy \quad (12)$$

where θ^1 denotes the change in monthly ocean temperature and $\bar{\mathbf{v}}_1$ denotes the monthly climatological Eulerian-mean velocity in the preindustrial control run. It is worth noting that the

above approach (Eqs. 11-12) may not serve as a strict decomposition of ocean circulation- and temperature-driven components given that anthropogenic temperature signal may not appear as a quasi-passive tracer in some regions, which potentially contributes to the large uncertainties as shown in Fig. 4.

Southern Ocean MOCs

The Eulerian-mean MOC ($\bar{\psi}$) or the “Deacon Cell” is computed through the zonal and vertical integrations of the Eulerian-mean meridional velocity $\bar{v}$:

$$\bar{\psi} = \oint \int_l^l \bar{v} dz' dx \quad (13)$$

The eddy-induced MOC (ψ^*) is computed through the zonal and vertical integrations of the meso- plus sub-mesoscale eddy-induced meridional velocity v^* :

$$\psi^* = \oint \int_l^l v^* dz' dx \quad (14)$$

The residual MOC ($\psi_{!}^{\#}$) is calculated as

$$\psi_{!}^{\#} = \bar{\psi} + \psi^* \quad (15)$$

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Data availability

CMIP5 model (except CESM1-CN) data are available at <https://esgf-node.llnl.gov/projects/cmip5/> and CMIP6 data are available at <https://esgf-node.llnl.gov/projects/cmip6/>. The DePreSys data are available at <ftp://ftp-icdc.cen.uni-hamburg.de/EASYInit/DePreSys/>. The EN4 (version 4.2.2) data are available at <http://www.metoffice.gov.uk/hadobs/en4/index.html>. The IAP data are available at <http://www.ocean.iap.ac.cn/>. The data from the research led by Ishii (version 7.3.1) are available at <https://climate.mri-jma.go.jp/pub/ocean/ts/v7.3.1/temp/>. The GECCO3 data are available at <http://icdc.cen.uni-hamburg.de/en/gecco3.html>. The ORAS4 data are available at <https://icdc.cen.uni-hamburg.de/daten/reanalysis-ocean/easy-init-ocean/ecmwf-ocean-reanalysis-system-4-oras4.html>.

Code availability

The source code of CESM1-CN is available at <https://www.cesm.ucar.edu/>. Figures are generated via the NCAR Command Language (NCL, Version 6.5.0) [Software]. (2018). Boulder, Colorado: UCAR/NCAR/CISL/TDD. <http://dx.doi.org/10.5065/D6WD3XH5>

The codes and processed data to generate Figures 1-6 are available at Zenodo. DOI:10.5281/zenodo.7939155

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