

**Enhanced upper ocean warming projected by the eddy-resolving Community Earth System Model**

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**Key points**

- Simulated upper-ocean ocean heat content anomalies are more realistic in high-resolution simulations than in low-resolution counterparts.
- With similar ocean surface heating, high-resolution simulations project stronger upper-ocean warming than low-resolution simulations.
- Future changes in vertical heat transport depend on the representation of the mean ocean states at present day.

## Abstract

Ocean warming is a key factor impacting future changes in climate. Here we investigate vertical structure changes in globally averaged ocean heat content (OHC) in high- (HR) and low-resolution (LR) future climate simulations with the Community Earth System Model (CESM). Compared with observation-based estimates, the simulated OHC anomalies in the upper 700 m and 2000 m during 1960-2020 are more realistic in CESM-HR than -LR. Under RCP8.5 scenario, the net surface heat into the ocean is very similar in CESM-HR and -LR. However, CESM-HR has a larger increase in OHC in the upper 250 m compared to CESM-LR, but a smaller increase below 250 m. This difference can be traced to differences in eddy-induced vertical heat transport between CESM-HR and -LR in the historical period. Moreover, our results suggest that with the same heat input, upper-ocean warming is likely to be underestimated by most non-eddy-resolving climate models.

## Plain language summary

With the rise in anthropogenic emissions, the ocean has absorbed over 90% of greenhouse gas-related heat, resulting in well-known ocean warming. This warming is the main cause of severe deoxygenation, coral bleaching, and sea-level rise, among others. Furthermore, the upper ocean experiences more warming than the deep ocean, which leads to strengthened ocean stratification. On a global scale, the heat into the ocean is vertically redistributed by a downward mean-flow-induced heat transport, upward eddy-induced heat transport, and vertical turbulent mixing. In this study, we compare vertical structures of ocean heat uptake in response to anthropogenic forcing between high (~10 km) and low horizontal resolution (~100 km) future climate simulations. We find that, with similar heat input at the ocean surface, the high-resolution simulations exhibit more warming in the upper 250 m of the ocean than their low-resolution counterparts. This difference is caused by the different representations of vertical heat transport by mesoscale ocean eddies in high- and low-resolution models.

## 1. Introduction

The increase in anthropogenic greenhouse gas (GHG) emissions has led to an increase in ocean stratification due to uneven warming at different depths (Capotondi et al., 2012; Li et al., 2020; Yamaguchi & Suga, 2019). This trend is projected to continue (Bopp et al., 2013; Moore et al., 2018), and could negatively impact the deep ocean's ability to absorb carbon dioxide from the atmosphere (Bourgeois et al., 2022). Moreover, warmer seawater holds less soluble oxygen, and the enhanced ocean stratification weakens oxygen exchanges between the upper and deep ocean (Helm et al., 2011; Keeling et al., 2010; Schmidtke et al., 2017), resulting in reduced net primary and export production (Fu et al., 2016). In addition, ocean warming is responsible for coral bleaching (Bleuel et al., 2021; Cantin et al., 2010; Frieler et al., 2013), poleward shifts of fish species (Perry et al., 2005; Pinsky et al., 2013), and sea level rise (Church et al., 2011; Domingues et al., 2008; Levitus et al., 2012). It is, therefore, imperative to improve our capability to skillfully project future changes in upper-ocean warming.

Observational studies have shown that more than 90% of heat generated by human activities has been absorbed by the ocean during the historical period (Cheng et al., 2019; Gattuso et al., 2015; Rhein et al., 2013; Trenberth et al., 2014), with around 87% of it stored in the upper 2000 m (Cheng et al., 2017). This heat has mainly been distributed in the upper 700 m prior to 1990 and has gradually moved into the deep ocean in the more recent period (Chen & Tung, 2014; Cheng et al., 2017). However, projecting future changes in ocean temperature directly from these observations remains challenging due to the short record length and large natural climate variability. Climate models have, therefore, become crucial tools for understanding and predicting future ocean warming and stratification.

Modeling studies have demonstrated that vertical heat transport (VHT) along with vertical turbulent-mixing-induced heat fluxes plays a critical role in determining the vertical distribution of ocean heat and consequently influencing ocean stratification (Griffies et al., 2015; Wolfe et al., 2008). VHT encompasses upward eddy-induced heat transport (EVHT) and downward mean-flow-induced heat transport (MVHT). EVHT tends to increase upper ocean temperature, while MVHT tends to decrease it. Therefore, accurately representing these ocean processes in climate models is essential for simulating and projecting future changes in ocean stratification.

However, most of climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) do not explicitly resolve ocean eddies due to their low horizontal resolution of approximately  $1^\circ$ . Instead, they parameterize eddy-induced heat fluxes (Fox-Kemper et al., 2008; Gent & McWilliams, 1990). Previous studies (Flato et al., 2013; Kuhlbrodt & Gregory, 2012) have shown that these models generally exhibit less stratification compared to observations in the upper 2000 m. In contrast, recent investigations (Chang et al., 2020) based on simulations using the Community Earth System Model (CESM) have revealed that explicitly representing mesoscale eddies by increasing the ocean model's horizontal resolution to approximately  $0.1^\circ$  enhances global-mean ocean stratification, especially in the upper 1000 m. Similar findings have been seen in other high-resolution climate model studies (Griffies et al., 2015; Roberts et al., 2019). The mean ocean stratification has been further shown to constrain heat uptake efficiency in the Southern Ocean (Bourgeois et al., 2022). These results motivate us to investigate whether the representation of explicitly resolved versus parameterized eddy fluxes in high- and low-resolution climate models, respectively, is the primary factor contributing to such differences in future projections of global ocean stratification changes through modulating vertical heat distributions.

## **2. Data and Methods**

### **2.1 CESM simulations**

Both the high- and low-resolution CESM (CESM-HR and CESM-LR, respectively) simulations used in this study were performed using CESM version 1.3 (Chang et al., 2020, 2023; Meehl et al., 2019; Small et al., 2014). In the present study, we make use of the following CESM-HR simulations: a 500-year-long pre-industrial control (PI-CNTL) simulation run under constant 1850 forcing conditions; a historical-future transient (HF-TNST) simulation for the 1850-2100 period that started from year 250 of PI-CNTL; and two additional HF-TNST ensemble members for the 1920-2100 period, which were branched from the 1850-2100 HF-TNST at year 1920 with

roundoff-level perturbations added to the atmospheric potential temperature initial conditions. These HF-TNST simulations use historical forcings from 1850 to 2005, followed by RCP8.5 forcings from 2006 to 2100. We also employ the corresponding LR simulations which have 5 HF-TNST ensemble members.

OHC change ( $\Delta\text{OHC}$ ) is defined as the OHC in HF-TNST after subtracting the linear trend of OHC in PI-CNTL, to ensure that the impact of model drift is largely removed (see Section 2.3 below). This approach assumes that the model drift remains unchanged in both HF-TNST and PI-CNTL. In addition, this study defines eddies as the departure from seasonal-mean in CESM-HR to construct eddy vertical heat transport (EVHT). However, conclusions will keep the same if using monthly mean to define eddy. The EVHT change ( $\Delta\text{EVHT}$ ) is defined as the difference between mean EVHT in HF-TNST and PI-CNTL.

## 2.2 Observation-based data and CMIP5 simulations

To validate the CESM simulations during the historical period from 1960 to 2020, we compare them with observation-based ocean heat content (OHC) estimates from three different sources: Institute of Atmospheric Physics (IAP) (Cheng et al., 2017), Japan Meteorological Agency (JMA) (Ishii et al., 2017), and NOAA (Levitus et al., 2012). In addition, 20 coupled climate models participating in CMIP5 (see Table S1) are used to compare with CESM results. In the comparative analysis, we made a deliberate decision not to include CMIP6 simulations due to potential complications arising from different emission forcings used in CESM-HR and CMIP6 simulations.

## 2.3 Heat Budget Analysis

The potential temperature equation in Cartesian coordinates is given by

$$\frac{\partial T}{\partial t} = -\frac{\partial(uT)}{\partial x} - \frac{\partial(vT)}{\partial y} - \frac{\partial(wT)}{\partial z} + \frac{1}{c_P \rho_0} \frac{\partial Q}{\partial z} + \kappa_H \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) T + \frac{\partial}{\partial z} \kappa_v \left( \frac{\partial T}{\partial z} - \gamma_x \right), \quad (1)$$

where  $T$  is the potential temperature;  $u$ ,  $v$ , and  $w$  are the total velocity components along the  $x$  (longitude),  $y$  (latitude), and  $z$  (vertical; positive upwards) axes;  $Q$  is the heat flux (positive downward) including solar and nonsolar components;  $c_P=3996$  J/kg/°C is the heat capacity of seawater;  $\rho_0$  is the density of seawater taken as 1026 kg/m<sup>3</sup>;  $\kappa_H$  and  $\kappa_v$  are the horizontal and vertical diffusivities;  $\gamma_x$  represents the nonlocal term in the K-Profile Parameterization (KPP) (Large et al., 1994). On the right-hand side (RHS) of Eq. 1, the first three terms represent the convergence of total heat transport, which includes resolved and parameterized heat transport in CESM-LR and only the resolved heat transport in CESM-HR. The remaining terms denote the atmospheric heating and horizontal and vertical turbulent mixing, respectively.

After integrating Eq. 1 in latitude and longitude space over the global ocean, all horizontal oceanic processes vanish, and the equation reduces to:

$$\frac{\partial \langle T \rangle}{\partial t} = -\frac{\partial \langle wT \rangle}{\partial z} + \frac{1}{c_P \rho_0} \frac{\partial \langle Q \rangle}{\partial z} + \frac{\partial}{\partial z} \left\langle \kappa_v \left( \frac{\partial T}{\partial z} - \gamma_x \right) \right\rangle, \quad (2)$$

where the angle bracket  $\langle \cdot \rangle$  represents the horizontal integration operator. The evolution of the global-mean temperature can be obtained by integrating Eq. 2 in time:

$$\langle T(z, t) \rangle - \langle T(z, 0) \rangle = \int_0^t \frac{-\partial \langle wT \rangle}{\partial z} dt + \int_0^t \frac{1}{c_P \rho_0} \frac{\partial \langle Q \rangle}{\partial z} dt + \int_0^t \frac{\partial}{\partial z} \left( \kappa_v \left( \frac{\partial T}{\partial z} - \gamma_x \right) \right) dt. \quad (3)$$

After multiplying Eq. 3 by  $c_P \rho_0$  and integrating between a given depth  $h$  below the ocean surface (below the shortwave penetration depth) and the seafloor  $H$ , the equation governing OHC from  $H$  to  $h$  is

$$\langle OHC(t) \rangle - \langle OHC(0) \rangle = -c_P \rho_0 \int_0^t \langle wT \rangle|_{z=-h} dt + c_P \rho_0 \int_0^t \left( \kappa_v \left( \frac{\partial T}{\partial z} - \gamma_x \right) \right)|_{z=-h} dt,$$

(4)

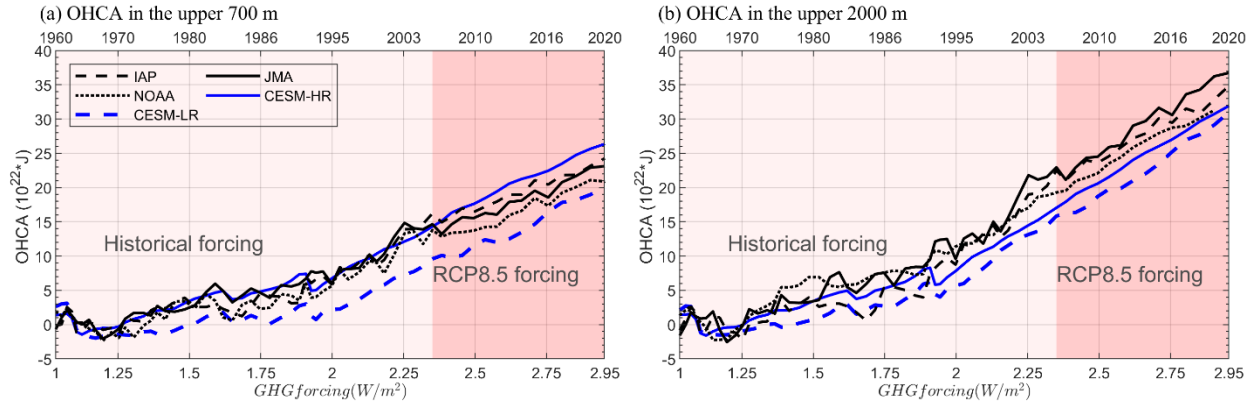
where the term on the left-hand side (LHS) of Eq. 4 is a timeseries of OHC ( $c_P \rho \int_{-H}^{-h} \langle T(z, t) \rangle dz$ ) anomaly relative to its value at  $t=0$ . The terms on the RHS are contributions from the global-mean VHT and vertical mixing at  $z=-h$ . The surface heat flux term in Eq. 3 does not appear in Eq. 4 because the net atmospheric heating, including the penetrative shortwave radiation, is zero at depths of interest in this study, e.g., below 250 m. In the following analysis, the vertical turbulent mixing term will be calculated as a residual of the other terms in Eq. 4.

To compute the OHC response to greenhouse gas forcing, we first calculate each term in Eq. 4 in both PI-CNTL and HF-TNST, and then perform a linear regression analysis to each term in PI-CNTL. Finally, we subtract the PI-CNTL linear trend from each term of Eq. 4 in HF-TNST to remove the impact of model drift.

### 3. Results

#### 3.1 Simulated OHC against observation-based estimates

Following Levitus et al. (2012), we first validate simulated OHC against observation-based estimates for the upper 700 m and upper 2000 m. In the upper 700 m, the OHC anomaly (OHCA), defined as departure from the mean over the period of 1960-1970, shows a broad agreement among the three observation-based products with values reaching  $21 \times 10^{22} \sim 25 \times 10^{22}$  J at the end of 2020 (Fig. 1). CESM-HR agrees better with these products than CESM-LR during 1960-2005, but CESM-HR (CESM-LR) overestimates (underestimates) OHCA during 2006-2020. The warming rate of OHC in the upper 700 m from 1960-2020 is  $0.37 \text{ W/m}^2$  in CESM-HR and  $0.26 \text{ W/m}^2$  in CESM-LR. The observation-based estimates of  $0.31\text{-}0.35 \text{ W/m}^2$ , consistent with those reported in the IPCC reports (Bindoff et al., 2019), are closer to the value in CESM-HR than that in CESM-LR.



**Fig. 1. OHCA in observation-based estimates and CESM.** (a) OHCA in the upper 700 m and (b) 2000 m estimated by IAP (black dashed), JMA (black solid), NOAA (black dotted), CESM-HR (blue solid), and CESM-LR (dashed blue). Baseline is the mean over 1960-1970. The bottom x-axis shows the GHG-induced radiative forcing ( $\text{W/m}^2$ ) under RCP8.5 emission scenario and the top x-axis shows the corresponding time (years).

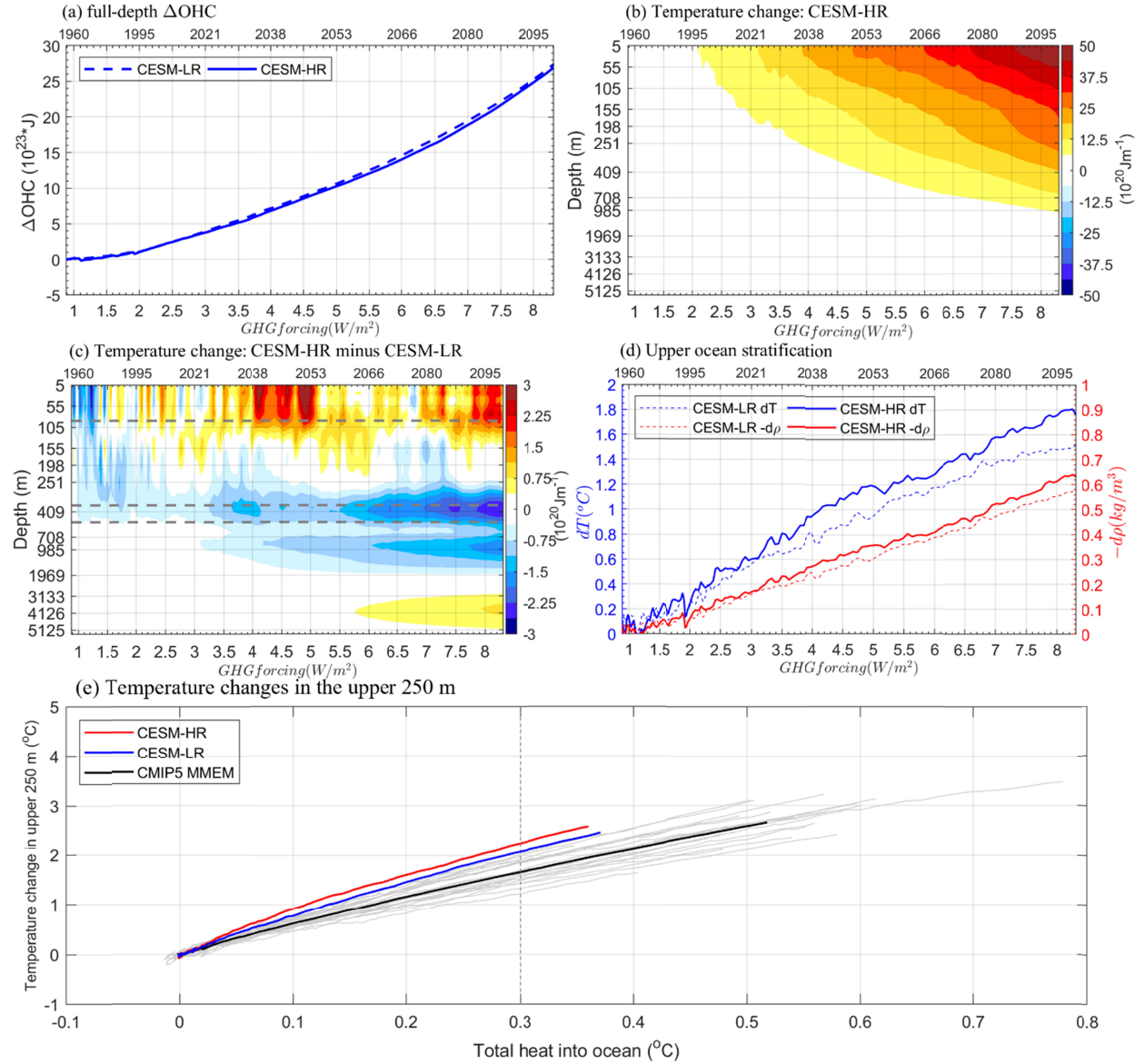
In contrast to OHCA in the upper 700 m, the simulated OHCA in the upper 2000 m tends to be lower than those of the observation-based products in both CESM-HR and CESM-LR, particularly after the 1991 Mount Pinatubo eruption. However, CESM-HR values are consistently higher than those of CESM-LR and closer to the observation-based estimates. Interestingly, the difference in OHCA between CESM-HR and CESM-LR in the upper 2000 m is smaller than that in the upper 700 m, especially after early 1990s, suggesting some cancellation of differences above and below 700 m. The estimated warming rate of OHC in the upper 2000 m from 1960-2020 is between 0.46 and 0.53  $\text{W/m}^2$  in observation-based data, 0.45  $\text{W/m}^2$  in CESM-HR, and 0.42  $\text{W/m}^2$  in CESM-LR.

After comparing the simulated OHC in CESM-HR and CESM-LR against observation-based estimates, we can conclude that both models perform reasonably well in reproducing OHCA over the historical period in the upper ocean, with CESM-HR being closer to the observation-based estimates than CESM-LR. Moving forward, our focus will be on analyzing the projected future changes in OHC in both model configurations and assessing the impact of model resolution on global ocean warming and associated stratification changes.

### 3.2 Globally-averaged ocean temperature projections

The full-depth integrated global-mean  $\Delta\text{OHC}$  in CESM-HR and CESM-LR closely aligns with each other from 1950 to 2100 (Fig. 2a), suggesting that horizontal resolution differences in CESM have a negligible impact on the total ocean heat uptake. Under RCP8.5 forcing, both CESM-HR and CESM-LR project a warming rate of 2.56  $\text{W/m}^2$  over the 2020-2100 period, with a net ocean heat uptake of  $27 \times 10^{23}$  J by the end of 2100, representing a sevenfold increase from 2020. Because the total ocean heat uptake is directly related to the accumulated net surface heat flux over the global ocean, it means that CESM-HR and CESM-LR simulate remarkably similar amounts of net heat input into the ocean, despite their resolution differences. However, this does

not indicate that the vertical distribution of the ocean heat uptake will also be similar between CESM-HR and CESM-LR.



**Fig. 2. Projected ocean temperature changes in CESM and CMIP5 models.** (a) Full-depth integrated  $\Delta\text{OHC}$  in CESM-LR (dashed) and CESM-HR (solid); (b) ocean temperature changes (scaled with horizontal ocean areas,  $c_p$  and  $\rho_0$ ) as a function of depth in CESM-HR; (c) similar to (b) but for CESM-HR minus CESM-LR; (d) upper ocean temperature difference between 0-100 m and 350-450 m ( $dT$ , blue; left axis) and upper ocean density difference ( $-d\rho$ , red; right axis) in CESM-LR (dashed) and CESM-HR (solid), with positive values indicating increases in stratification. Note that the y-axis in (b-c) is a linear function of vertical layer number in CESM, instead of depth. Grey dashed lines in (c) represent depths of 100 m, 350 m, and 450 m, respectively. The bottom x-axis shows the GHG-induced radiative forcing ( $\text{Wm}^{-2}$ ) under RCP8.5

emission scenario and the top x-axis shows the corresponding time (years) starting from the year 1950. Results in (b-c) with the unit of  $^{\circ}\text{C}$  are shown in Fig. S1a-b, respectively. (e) Relationship of total heat into ocean and temperature changes (relative to the mean over 1950-1960) in the upper 250 m. Red, blue, gray, and black lines in (e) represent results from CESM-HR, CESM-LR, CMIP5 models, and CMIP5 multi-model ensemble mean (MMEM), respectively. CMIP5 models are forced by RCP8.5 from 2006-2100.

Fig. 2b shows global-mean ocean temperature changes relative to its PI-CNTL as a function of depth and time in CESM-HR. The warming is relatively weak before 2000 with less than  $2.1 \text{ W/m}^2$  of GHG-induced radiative forcing. The warm temperature anomaly gradually penetrates deeper, reaching a depth of about 1000 m by the end of 2100, indicating an increase in the upper ocean thermal stratification in the future as expected. These warming characteristics in CESM-HR also hold in CESM-LR (Fig. S1), except that less warming is observed in the upper 250 m, but more below 250 m in CESM-LR than in CESM-HR (Fig. 2c). We note that there are strong internal variabilities in the upper 250 m. After using the signal-to-noise-maximizing EOF filter to reduce internal variability (Wills et al., 2020), the stronger warming of the upper 250 m in CESM-HR is more evident compared to CESM-LR (Fig. S2c). This result indicates that the GHG-induced heat is moved into the deep ocean at a faster rate in CESM-LR than in CESM-HR. Therefore, future changes in ocean stratification projected by CESM-HR and CESM-LR are different.

Upper ocean thermal (density) stratification changes can be estimated by taking the difference between potential temperature (density) averaged over the top 100 m and that over 350-450 m, denoted as  $dT$  ( $-d\rho$ ). These depth ranges are chosen mainly because the temperature differences between CESM-HR and CESM-LR peak within these depth ranges (Fig. S3). As expected,  $dT$  is increasing faster in CESM-HR than CESM-LR (Fig. 2d). Over the period of 2090-2100, the  $dT$  increase in CESM-HR is more than 20% higher than that in CESM-LR. The overall increasing trend of  $dT$  from 1950 to 2100 is 19% larger in CESM-HR than CESM-LR. This confirms that increasing horizontal resolution in CESM does have an impact on the representations of upper-ocean thermal stratification changes in the future. Upper-ocean density stratification changes, estimated by  $-d\rho$ , follow closely the  $dT$  changes (Fig. 2d), indicating that density stratification changes are dominated by temperature changes globally, in agreement with observation-based results (Li et al., 2020). These results are also more evident after applying signal-to-noise-maximizing EOF filter (Fig. S2d).

To further validate these CESM results, we analyze simulations from models participating in CMIP5. Because the vertical heat redistribution can be influenced by both the atmospheric heat input (i.e., the net surface heat flux) and vertical heat transport processes in the ocean, we here show the temperature change (relative to the 1950-1960 mean) in the upper 250 m ( $\Delta T_{250\text{m}}$ ) as a function of total heat into the ocean, expressed as ocean temperature change, from 1950-2100 (Fig. 2e). Different models simulate different amounts of heat into the ocean at the end of year 2100 (end points of each line), ranging from  $0.35^{\circ}\text{C}$  to  $0.78^{\circ}\text{C}$ , which is primarily determined by the respective models' climate sensitivity (Andrews et al., 2012; Zelinka et al., 2020). With the

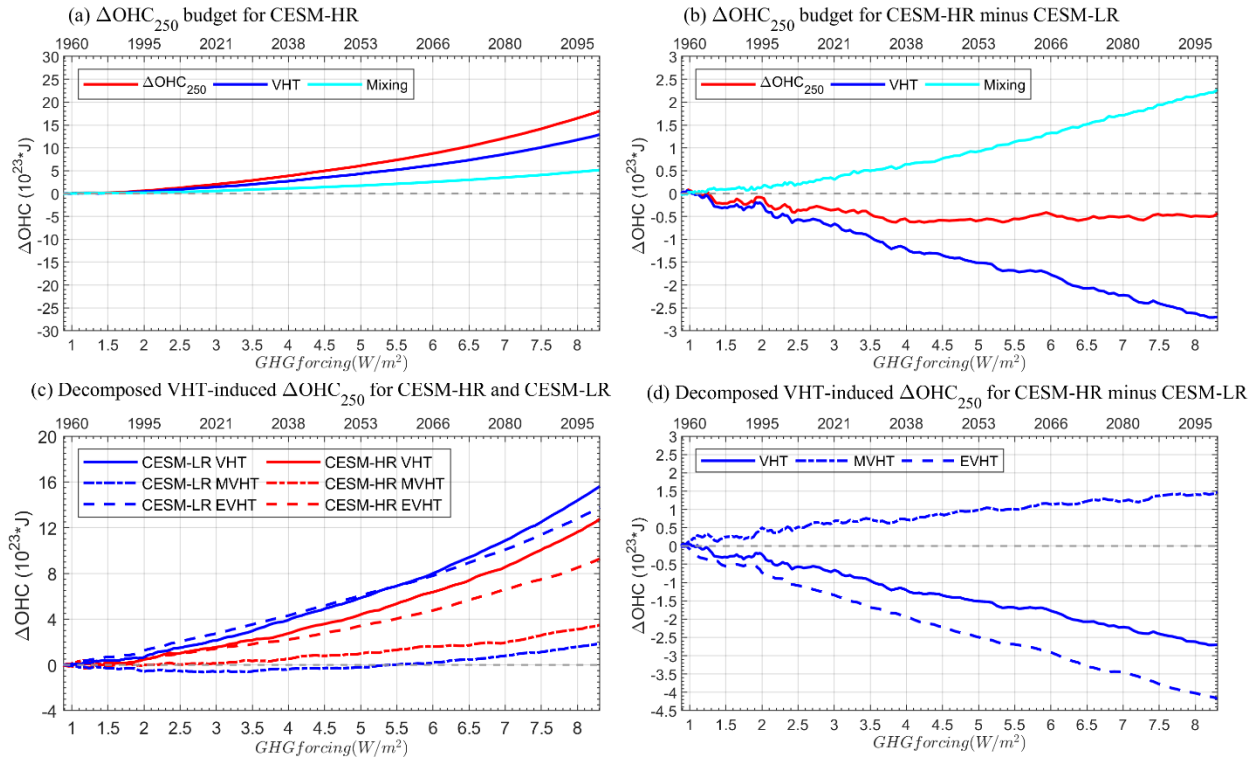


same RCP8.5 forcing,  $\Delta T_{250m}$  in CESM-HR lies outside of the spread of the CMIP5 ensemble, indicating that  $\Delta T_{250m}$  projected by CESM-HR increases faster than not only CESM-LR but also all other non-eddy-resolving models.

### 3.3 Role of resolved vs. parameterized eddy fluxes in vertical heat redistribution

To further investigate why more heat is transported to the deep ocean in non-eddy-resolving simulations than in eddy-resolving simulations, we conduct a global-mean heat budget analysis below 250 m in CESM-HR and CESM-LR (Fig. 3), where the ocean temperature rises faster in CESM-LR than in CESM-HR without strong influences of internal variability at interannual-to-decadal timescales (Fig. 2c). A similar analysis can be applied to the upper 250 m except that the strong internal variability in the upper ocean makes the interpretation of the results more difficult. The integrated  $\Delta OHC$  from 250 m to the bottom in CESM-HR, denoted as  $\Delta OHC_{250}$ , shows a monotonic increase (red), primarily driven by the increase in VHT (blue) with a smaller contribution from the vertical turbulent mixing (cyan) (Fig. 3a). These two oceanic processes are responsible for transporting heat from the top 250 m into the deeper ocean. By the end of 2100,  $\Delta OHC_{250}$  in CESM-HR is increased by  $18 \times 10^{23}$  J heat relative to 1950, roughly 72% of which is attributable to VHT.

Fig. 3b shows the difference in each term in the heat budget between CESM-HR and CESM-LR.  $\Delta OHC_{250}$  is always smaller in CESM-HR than CESM-LR (red), indicating less warming below 250 m in CESM-HR than in CESM-LR. This difference in  $\Delta OHC_{250}$  between CESM-HR and CESM-LR is attributable to VHT, which transports less heat to the deep ocean in CESM-HR than CESM-LR. The vertical turbulent mixing induced  $\Delta OHC_{250}$  difference between CESM-HR and CESM-LR significantly compensates the difference due to VHT.

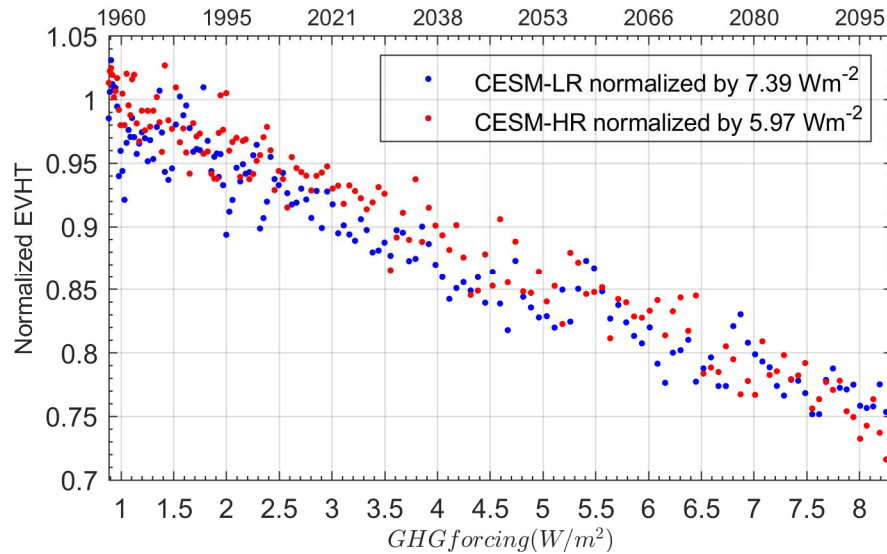


**Fig. 3. Globally averaged  $\Delta\text{OHC}$  balance for the layer below 250 m.** Budget in (a) CESM-HR and (b) CESM-HR minus CESM-LR. In (a-b), red for  $\Delta\text{OHC}_{250}$ , blue for VHT, and cyan for vertical mixing. (c) Decomposition of VHT-induced  $\Delta\text{OHC}_{250}$  in CESM-HR (red) and CESM-LR (blue). (d) Differences in the decomposed VHT-induced  $\Delta\text{OHC}_{250}$  between CESM-HR and CESM-LR. In (c-d), solid for total VHT, dot-dashed for MVHT, and dashed for EVHT.

Previous studies have shown that VHT results from the balance between upward EVHT and downward MVHT (Griffies et al., 2015; von Storch et al., 2016; Wolfe et al., 2008), which is also demonstrated in Fig. S4a. EVHT cools the layer below 250 m, while MVHT warms it. Fig. 3c shows that as GHG emissions increase, the cooling effect of EVHT decreases, while the warming effect of MVHT increases. Both EVHT and MVHT lead to more heat being transported into the deep ocean by VHT (Fig. 3c). However, the difference in VHT change between CESM-HR and CESM-LR is mainly caused by the weaker reduction of EVHT in CESM-HR than in CESM-LR (Fig. 3d). At the same time, the downward MVHT increases faster in CESM-HR than in CESM-LR, which partially compensates for the CESM-HR and CESM-LR differences in EVHT changes by about 37% at the end of year 2100. Therefore, representations of EVHT in climate models are very important to accurately simulate future vertical heat distributions, as well as ocean stratification.

To understand the role of mesoscale eddy fluxes, it is important to note that they serve to stratify the ocean by slumping isopycnals, thereby reducing the available potential energy (Gent & McWilliams, 1990). In CESM-LR, the parameterized EVHT is represented by the Gent-McWilliams parameterization (GM) (Gent & McWilliams, 1990; Griffies, 1998), which depends on the thickness diffusivity controlled by ocean stratification, isopycnal slope, and horizontal temperature gradient. In PI-CNTL, CESM-LR simulations have weaker ocean stratification than CESM-HR simulations (Fig. S4b), which results in more available potential energy. Therefore, the global average of parameterized EVHT at 250 m in CESM-LR ( $7.39 \text{ Wm}^{-2}$ ) is larger than the resolved EVHT in CESM-HR ( $5.97 \text{ Wm}^{-2}$ ) when averaged over year 350-500 of PI-CNTL.

While the EVHT reduction in HF-TNST is weaker in CESM-HR than CESM-LR, this difference becomes much smaller after normalizing EVHT by their respective mean values in PI-CNTL (Fig. 4), indicating that GM represents similar percentage changes of mean EVHT in PI-CNTL in CESM-LR as in CESM-HR in response to GHG forcing. By the end of year 2100, both the parameterized (CESM-LR) and resolved (CESM-HR) EVHT are decreased by 25% relative to their respective mean values in PI-CNTL. This proportional relationship between future changes in EVHT and mean EVHT also holds at other depths where most mesoscale eddies are generated (Fig. S5). This result leads us to hypothesize that the different EVHT responses to GHG forcing between CESM-HR and CESM-LR, which have a significant impact on ocean stratification changes, may be directly related to the difference in the mean EVHT in PI-CNTL between CESM-HR and CESM-LR. The smaller mean EVHT in CESM-HR that corresponds to stronger ocean stratification and less available potential energy in PI-CTNL causes a proportionally weaker EVHT decrease in response to the future warming, resulting in more heat being trapped in the upper ocean, and thus stronger ocean stratification increase in CESM-HR compared to CESM-LR.



**Fig. 4. Globally averaged EVHT at 250 m in CESM-LR and CESM-HR.** EVHT at 250 m in CESM-LR (blue) and CESM-HR (red) are normalized by the respective mean in PI-CNTL.

#### 4. Conclusions and Discussion

This study focuses on analyzing the vertical distribution of global mean ocean heat uptake specifically under the RCP8.5 high emission scenario. The analysis was conducted on an ensemble of CESM-HR simulations and compared to its CESM-LR counterpart. The results show that CESM-HR simulates stronger increase in upper-ocean stratification, even though the full-depth integrated ocean heat uptake is very similar between CESM-HR and CESM-LR. A comparison with other low-resolution climate model simulations participated in CMIP5 shows that this result holds for not only the CESM simulations, but also other models, suggesting that non-eddy-resolving climate models may underestimate the rate of future upper ocean stratification changes in response to GHG forcing. We would like to point out that with the same heat into the ocean, the upper ocean thermal stratification  $dT$  in CESM-HR increases faster than not only CESM-LR but also a vast majority of models participating in CMIP5 (Fig. S6).

A further comparative analysis of global-mean ocean heat budget reveals that the disparity in the upward EVHT serves as a major contributing factor to the divergence between CESM-HR and CESM-LR. The analysis demonstrates that CESM-LR exhibits a more rapid future decrease in EVHT, resulting in greater ocean heat uptake being transported into the deep ocean. We hypothesize that this discrepancy in EVHT response between CESM-HR and CESM-LR stems directly from the representation of mean EVHT in each model. In CESM-HR, the explicitly computed EVHT yields a smaller mean value compared to the parameterized EVHT in CESM-LR. This disparity corresponds to a stronger upper-ocean stratification and lower available potential energy in CESM-HR, potentially contributing to the comparatively weaker future decrease in EVHT when compared to CESM-LR. Further research is necessary to thoroughly examine and validate this hypothesis.

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## Open Research

Datasets from HF-TNST and PI-CNTL are available at [https://ihesp.github.io/archive/products/ihesp-products/data-release/DataRelease\\_Phase2.html](https://ihesp.github.io/archive/products/ihesp-products/data-release/DataRelease_Phase2.html). CMIP5 data are available at <https://esgf-node.llnl.gov/search/cmip5/>. IAP ocean heat content is available at <http://www.ocean.iap.ac.cn/pages/dataService/dataService.html?navAnchor=dataService>. NOAA ocean heat content is available at <https://www.ncei.noaa.gov/access/global-ocean-heat-content/>. JMA ocean heat content is available at [https://www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc\\_global\\_en.html](https://www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc_global_en.html). Analyses were conducted using Matlab.

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