

Change of the Global Ocean Vertical Heat Transport over 1993–2010

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ABSTRACT

A dynamically and data-consistent ocean state estimate during 1993–2010 is analyzed for bidecadal changes in the mechanisms of heat exchange between the upper and lower oceans. Many patterns of change are consistent with prior studies. However, at various levels above 1800 m the global integral of the change in ocean vertical heat flux involves the summation of positive and negative regional contributions and is not statistically significant. The nonsignificance of change in the global ocean vertical heat transport from an ocean state estimate that provides global coverage and regular sampling, spatially and temporally, raises the question of whether an adequate observational database exists to assess changes in the upper ocean heat content over the past few decades. Also, whereas the advective term largely determines the spatial pattern of the change in ocean vertical heat flux, its global integral is not significantly different from zero. In contrast, the diffusive term, although regionally weak except in high-latitude oceans, produces a statistically significant extra downward heat flux during the 2000s. This result suggests that besides ocean advection, ocean mixing processes, including isopycnal and diapycnal as well as convective mixing, are important for the decadal variation of the heat exchange between upper and deep oceans as well. Furthermore, the analyses herein indicate that focusing on any particular region in explaining changes of the global ocean heat content is misleading.

1. Introduction

The global-mean surface temperature has increased by about 0.85°C since the late nineteenth century (e.g., IPCC 2014). Although multidecadal trends are monotonically positive over this period, the rate of the warming is not uniform. Over the past hundred years, decadal slowdowns in global surface warming occurred between 1940 and 1975 and again since the beginning of the twenty-first century (e.g., Levitus et al. 2009; Meehl et al. 2011; Fyfe et al. 2016).

A number of mechanisms have been proposed to explain the apparent slowdown in global-mean surface warming in the 2000s. Besides explanations involving other components of the climate system, such as reduced solar radiation reaching the surface (e.g., Solomon et al. 2010; Santer et al. 2014) and methods of data analyses (e.g., Cowtan and Way 2014; Karl et al. 2015), at least three oceanic mechanisms have been emphasized. First, stronger than usual Pacific trade winds affected the vertical heat exchange between the upper and deep ocean and led to cooler tropical Pacific surface temperature (e.g., Kosaka and Xie 2013; England et al. 2014). Second, a stronger Atlantic meridional overturning circulation (AMOC) increased the heat uptake

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in the intermediate and deep oceans and led to a slowdown of the upper ocean warming (Chen and Tung 2014). Third, the heat redistribution within and/or between ocean basins may generate a global surface warming slowdown (e.g., Lee et al. 2015; Nieves et al. 2015; Liu et al. 2016).

While previous works highlight different components (e.g., wind-driven circulation or meridional overturning circulation) or regions (e.g., the North Atlantic or the tropical Pacific), they all share the assumption that changes in ocean vertical heat transport are central to changes in surface warming rates. However, contributions of the separate terms of ocean vertical heat transport (i.e., advection and diffusion) have not been carefully examined. Furthermore, oceanic heat uptake from the atmosphere is a global phenomenon, and owing to volume and other conservation rules, as well as the vertical dependence of ocean temperature, downward advection of heat in one region will tend to be at least partially compensated by an opposite upward heat advection elsewhere in the global ocean, thus leaving weaker residual impacts on the global integral. Thus, an increase in ocean advection of heat from the upper to the deep ocean in one region does not necessarily imply any changes in the global-mean upper ocean or deep ocean heat contents. At the same time, vertical heat transports associated with diffusive processes, despite being weaker regionally, could be important when considering global integrals.

The following questions thus emerge: do any or all previously proposed mechanisms contribute to leading order to the recent global surface temperature changes? What is the relative role of ocean diffusive processes in contributing to decadal changes in vertical ocean heat transport compared to vertical advection? Previous studies highlight different key ocean regions, such as the tropical Pacific and the North Atlantic. Does it make sense to claim that one region or another is “responsible” for the global surface warming slowdown? Addressing these questions will potentially clarify and improve our understanding of the role of ocean in the climate system, particularly in its decadal variability.

In this study, we will try to answer the above questions by analyzing a dynamically consistent ocean state estimate from Estimating the Circulation and Climate of the Ocean (ECCO), version 4 release 1 (v4r1). While the previous studies attributed the global surface warming slowdown to distinct ocean regions and mechanisms, they all involve the ocean vertical heat transport. Also, because of the strong mixing in the upper ocean, the surface temperature is closely related to the upper ocean heat content. Our analyses will therefore focus on the change in the ocean vertical

heat transport. This is a follow-up study of Wunsch and Heimbach (2014), in which ocean heat content changes were presented as a function of depth, and of Liang et al. (2015), in which only the time mean of ocean vertical heat flux was discussed. This present study is a first step at analyzing decadal changes with ECCO estimates, and motivated by the need to clarify the extent to which the slowdown in surface warming in the 2000s is compensated by an increase in interior ocean heating.

2. Data and processing

State-of-the-art ocean state estimates produced by the ECCO consortium can be interpreted as a least squares fitting of the Massachusetts Institute of Technology General Circulation Model (MITgcm; Adcroft et al. 2004) to the available global-scale ocean observations. In addition to being constrained by an enormous amount of data, ECCO estimates satisfy known equations of motion and conservation laws, so in contrast to ocean objective analyses (e.g., Ishii et al. 2005; Levitus et al. 2012) and ocean reanalyses (e.g., Balmaseda et al. 2013) that were previously used to investigate the supposed global surface warming slowdown (e.g., Nieves et al. 2015; Liu et al. 2016), no artificial internal sources and sinks are introduced through the data assimilation (e.g., Wunsch and Heimbach 2013a). Also, ECCO estimates make available not only temperature and salinity but also three-dimensional velocities and mixing parameters (e.g., Forget et al. 2015b) and can be used to conduct detailed budget analyses (e.g., Piecuch and Ponte 2014; Buckley et al. 2015).

In this study, we use the ECCO v4r1 estimate (Forget et al. 2015a) and analyze the net air–sea heat flux Q_{net} and the ocean vertical heat flux H_v . The ECCO v4r1 estimate covers the period 1992–2011, when altimetry measurements of high precision, quasi-global coverage of ocean in situ measurements, mainly Argo temperature and salinity profiles, and the WOCE hydrographic program and the follow-on hydrography, are available. Thus a decadal time scale of averaging and of change is accessible. This estimate has 1° nominal zonal resolution and varying resolution meridionally between about 0.25° and 1° . The vertical grid comprises 50 levels of increasing thickness with depth, with 10–20-m level spacing in the upper ocean.

The ECCO v4r1 estimates realistically represent the ocean state. Previous publications have demonstrated that the estimates fit altimetry (Forget and Ponte 2015), SST (Buckley et al. 2014), subsurface hydrography data (Forget et al. 2015a), and the Atlantic meridional overturning circulation (Wunsch and

Heimbach 2013b) at or close to the specified noise level. Many quantities (e.g., isopycnal mixing) for which no corresponding observations are available have been analyzed in some detail and found to be at least physically plausible (Forget et al. 2015b). An extensive documentation of model–data misfits and physical characteristics of the state estimate is publicly available.¹

The change of the upper ocean heat content is ultimately determined by air–sea heat exchange (i.e., Q_{net}) and the heat flux through its lower face. A priori forcing fields of ECCO v4r1 are from the ERA-Interim (Dee et al. 2011). Surface atmospheric fields (temperature, humidity, downward radiation, precipitation, and wind stress) are control parameters and are adjusted using the adjoint method (Forget et al. 2015a). Latent, sensible, and upward radiative components of Q_{net} are computed using the bulk formulas of Large and Yeager (2004) and the adjusted near-surface atmospheric fields. Thus, the ECCO v4r1 estimate of Q_{net} can be considered as an adjusted ERA-Interim estimate that is constrained by ocean dynamics and observations. Intercomparison with other leading flux products (Liang and Yu 2016) shows that ECCO v4r1 corrected a suspicious long-term trend in the ERA-Interim Q_{net} and displayed encouraging agreement with the OAFflux/CERES product (e.g., Yu and Weller 2007). For a detailed description and validation of Q_{net} , see Liang and Yu (2016).

The net ocean vertical heat flux below 200 m consists of advective H_a and diffusive H_d terms. Penetrating solar radiation appears in the upper 200 m and is important for the thermal structure there. Because we are mainly interested in the exchange between the upper and deep oceans, only H_a and H_d are considered. In the model, H_a consists of two parts: the Eulerian mean transport, $\rho C_p w(T - T_c)$, and the eddy-induced bolus transport, $\rho C_p w^*(T - T_c)$ (e.g., Gent and McWilliams 1990), where ρ is the density of the seawater, C_p is the specific heat of seawater at constant pressure, T is temperature, T_c is reference temperature, w is the Eulerian vertical velocity, and w^* is the bolus velocity. Note that the absolute values of H_a depend on the reference temperature but its global mean is independent of reference temperature when volume is conserved (e.g., Lee et al. 2004). We simply used a constant reference temperature of 0°C.

The vertical diffusive heat flux is calculated as

$$H_d = -\rho C_p \left[\underbrace{\left(k_{wx} \frac{\partial T}{\partial x} + k_{wy} \frac{\partial T}{\partial y} + k_{wz} \frac{\partial T}{\partial z} \right)}_{\text{rhs1}} + \underbrace{k_z \frac{\partial T}{\partial z}}_{\text{rhs2}} \right], \quad (1)$$

where rhs1 is contribution of the isopycnal diffusion to the vertical transport of temperature (Redi 1982); k_{wx} , k_{wy} , and k_{wz} are elements of the Redi tensor; k_z in rhs2 includes three components, the background diffusivity, which is adjusted through the adjoint process, the part parameterized using the mixing scheme of Gaspar et al. (1990), and the part related to the convective adjustment. The contribution of isopycnal mixing to vertical heat transport (rhs1) in the ocean occurs because vertical heat flux is calculated at distinct depth levels, whereas isopycnal mixing acts along tilted isopycnals. This feature can cause heat to diffuse upward in the ocean (e.g., Gregory 2000; Liang et al. 2015) and turns out to be particularly important in interpreting the change of the vertical diffusive heat flux. In addition, the global mean of the vertical heat flux that is due to isopycnal mixing shows a subsurface maximum, being close to 1.5 W m^{-2} , in ECCO v4r1 around 500-m depth. This value is consistent with an independent calculation based on the estimates of isopycnal diffusivity from Cole et al. (2015) and the World Ocean Atlas (WOA) climatology. A more detailed comparison between the along-isopycnal heat flux in ECCO v4r1 and that implied by the isopycnal diffusivity from Cole et al. (2015) will be presented in a separate study.

Estimates of Q_{net} and H_v as well as H_a and H_d were first averaged over the periods 1993–2001 and 2002–10, respectively. Then the corresponding differences between the two periods were calculated, representing their bi-decadal changes over 1993–2010. The uncertainties of the means of each variable are estimated as $\sigma/\sqrt{n_e}$, where σ is the standard deviation of the corresponding variable (with seasonal cycle removed) and n_e is the effective degrees of freedom. Autocorrelations of H_v , H_a , and H_d indicate that they can be approximately represented by autoregressive [AR(1)] processes. Values of n_e are thus calculated following Calafat and Chambers (2013) as $n_e = n[(1 - \rho)/(1 + \rho)]$, where ρ is the lag-1 autocorrelation coefficient determined from the time series with seasonal cycle removed and n is 108, the number of values within each period. Uncertainties of the differences between the two periods can, if independent, be approximately calculated as $\Theta = \sqrt{\sigma_{93-01}^2 + \sigma_{02-10}^2}$, where σ_{93-01} and σ_{02-10} are uncertainties of corresponding variables over 1993–2001 and 2002–10, respectively. Note that the uncertainty estimates only include the temporal variability

¹ See http://mit.ecco-group.org/ecco_for_las/version_4/release1/ancillary_data/standardAnalysis.pdf.

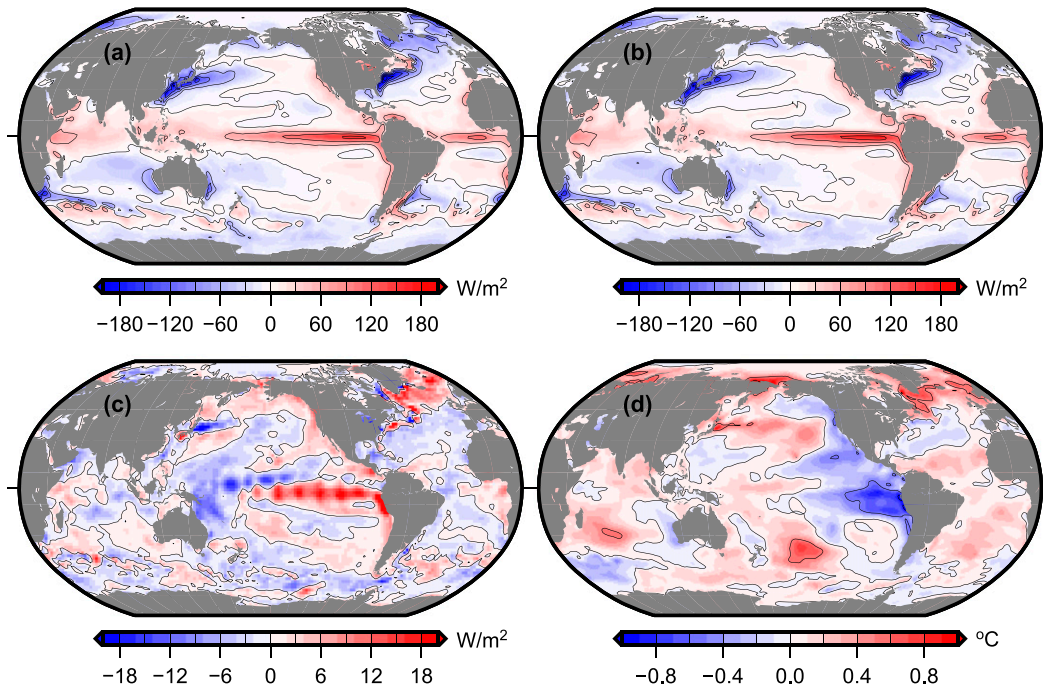


FIG. 1. Net air–sea heat flux and its change over 1993–2010. Nine-year averages of $\overline{Q}_{\text{net}}$ over (a) 1993–2001 and (b) 2002–10. Red (blue) means the ocean received (lost) heat. (c) Difference of the 9-yr averaged $\overline{Q}_{\text{net}}$ (2002–10 minus 1993–2001). Red stands for extra ocean heat uptake during 2002–10. (d) Difference of the 9-yr averaged SST (2002–10 minus 1992–2001). Note the varying ranges of different color bars.

but not the errors from models and observational data, and are likely lower bounds. Changes presented below are averages of 2002–10 minus those of 1993–2001. Similar calculations for periods 1993–2000 and 2001–07 were also carried out and conclusions were generally the same, demonstrating that our results are not overly sensitive to the chosen periods (cf. Fyfe et al. 2016).

3. Results

Nine-year means of the net air–sea heat flux $\overline{Q}_{\text{net}}$ (hereinafter the overbar represents time mean) over 1993–2001 and 2002–10 are displayed in Figs. 1a and 1b, respectively. Visually, $\overline{Q}_{\text{net}}$ maps over the two periods are strikingly similar. Both show the well-known spatial patterns of the ocean receiving heat at low latitudes and losing heat at high latitudes and of the ocean circulation, particularly the western boundary currents, playing a crucial role in the air–sea heat exchange. However, $\overline{Q}_{\text{net}}$ over these two periods does show interesting differences (Fig. 1c) and, despite its noisy details, displays clear large-scale patterns. During 2002–10, greater ocean heat uptake ($\sim 10 \text{ W m}^{-2}$) occurred in the eastern tropical Pacific and less heat ($\sim 10 \text{ W m}^{-2}$) was released to the atmosphere in the northern North Atlantic. The SST difference (Fig. 1d) shows a La Niña-like spatial structure, with

lower SST in the eastern tropical Pacific but higher SST in the western tropical Pacific, likely representing the impact of the 1997–98 El Niño event. The changes in $\overline{Q}_{\text{net}}$ and SST are generally consistent with previous studies (e.g., Meehl et al. 2011; Kosaka and Xie 2013). Nevertheless, it should be noted that there is a compensation of the cold eastern tropical Pacific by the warm western tropical Pacific. The spatial variations in the $\overline{Q}_{\text{net}}$ and SST changes produce a greatly diminished averaged contribution to the global surface cooling.

As with the net air–sea heat flux, the 9-yr averaged ocean vertical heat flux values \overline{H}_v over 1993–2001 and 2002–10 are almost visually identical (not shown). We will thus only focus on the small difference between them $d\overline{H}_v$ as well as the changes of the advective $d\overline{H}_a$ and diffusive $d\overline{H}_d$ terms. Figure 2 presents their spatial distributions at two sample depths, 200 and 700 m. At 200 m, a large portion of the global ocean shows clear changes in various places of both signs of up to $\sim 20 \text{ W m}^{-2}$ in the vertical heat flux (Fig. 2a). In addition to the previously highlighted eastern tropical Pacific (e.g., England et al. 2014) and the North Atlantic (Chen and Tung 2014), other subtropical oceans also show large changes. These features show that the impacts of changes in the ocean vertical heat flux can only be understood on a global basis. For example, the extra

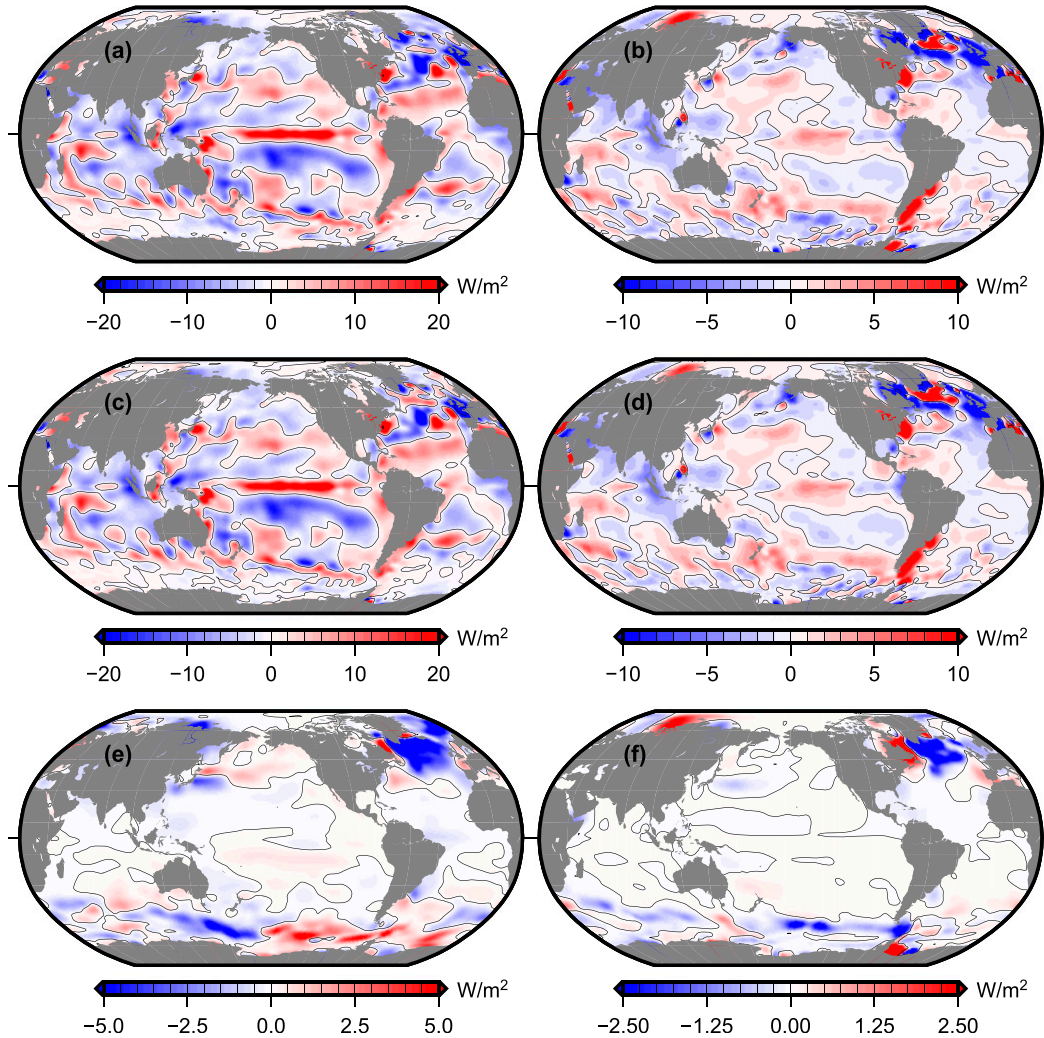


FIG. 2. Changes in ocean vertical heat flux and its major components over 1993–2010 at two sample depths: (left) 200 and (right) 700 m. (a),(b) Total ocean vertical heat flux; (c),(d) advective vertical heat flux; and (e),(f) diffusive vertical heat flux. Red (blue) stands for extra upward (downward) heat transport after 2001. Note the varying ranges of different color bars.

upward heat flux in the eastern tropical Pacific (Fig. 2c) is consistent with one previously proposed mechanism that the strengthened Pacific trade winds enhanced the upwelling in the eastern tropical Pacific (England et al. 2014), but related compensating changes are seen in the western and subtropical Pacific.

At 700 m, the spatial patterns of $d\bar{H}_v$ are very different from those at 200 m (Fig. 2b). The change of the vertical heat flux (up to 10 W m^{-2}) is generally smaller at 700 than at 200 m. The most pronounced feature at 700 m is that the largest change occurred at high latitudes, particularly in the northern North Atlantic, reflecting the crucial role of high-latitude regions in the heat exchange between upper and deep oceans. While patches of change can still be detected in the tropical Pacific, they are not as

significant as those in the North Atlantic. This relative loss of significance is generally consistent with Chen and Tung (2014), in which the authors showed that the Pacific Ocean heat content change is shallow and below 300 m the strongest vertical heat exchange occurs mostly in the subpolar North Atlantic and the Southern Oceans.

A visual examination of the contributions of the advective and diffusive terms to $d\bar{H}_v$ shows that the regional pattern of $d\bar{H}_v$ is largely determined by $d\bar{H}_a$ at both depth levels (Figs. 2c,d). The spatial correlations between $d\bar{H}_v$ and $d\bar{H}_a$ at 200 and 700 m are 0.96 and 0.97, respectively. In contrast, the spatial correlations between $d\bar{H}_v$ and $d\bar{H}_d$ at 200 and 700 m are just 0.25 and 0.19, respectively. The advective term is therefore important for the regional ocean vertical heat transport,

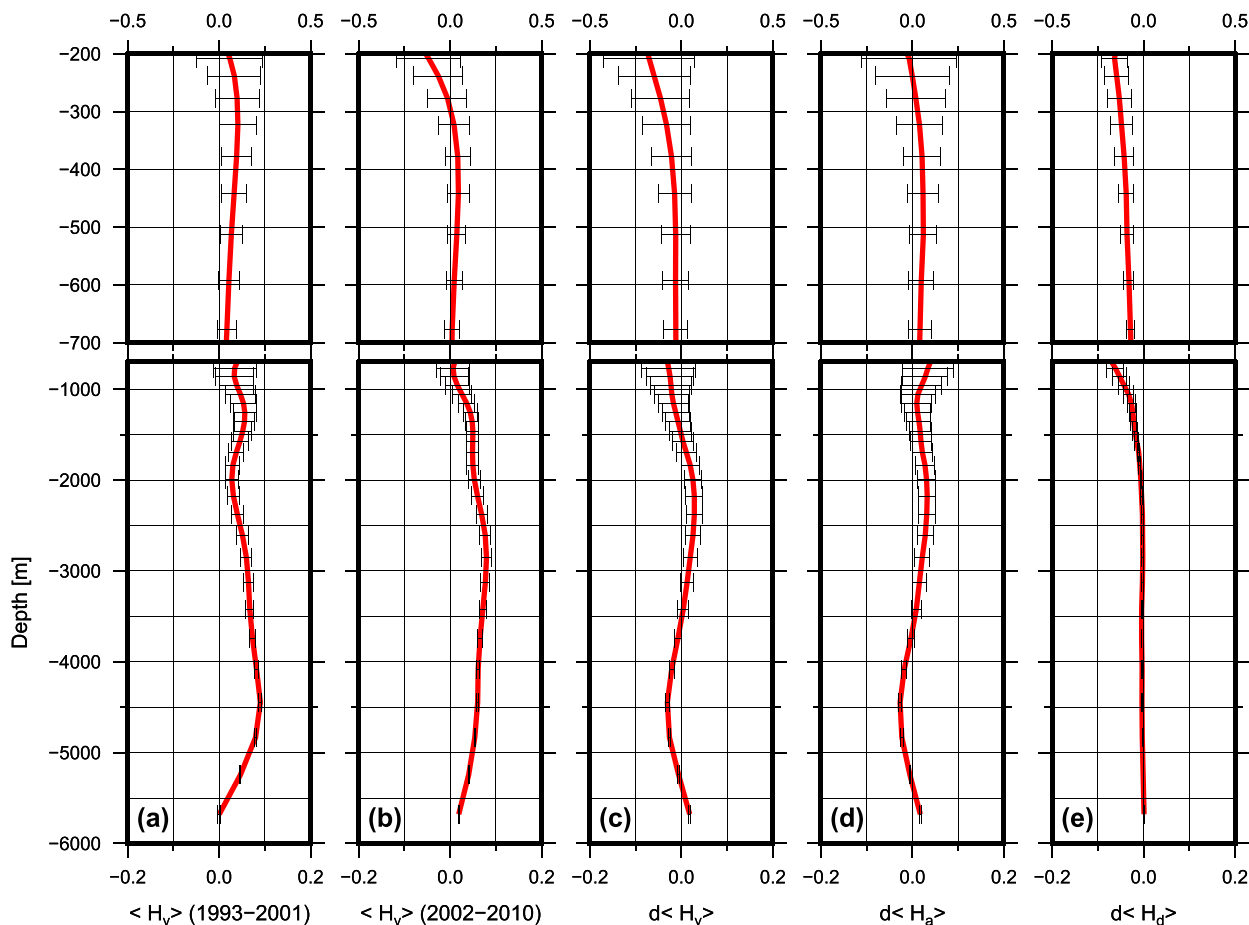


FIG. 3. Changes in global averaged ocean vertical heat transport (W m^{-2}). (a) Nine-year and global averages of the ocean vertical transport over 1993–2001. (b) As in (a), but for 2002–10. (c) The difference between the 9-yr and global averaged ocean vertical heat flux (2002–10 minus 1993–2001). (d) Change of the globally averaged advective vertical heat flux. (e) Change of the globally averaged diffusive vertical heat flux. Positive (negative) values stand for extra upward (downward) heat transport after 2001. Note that error bars represent 66% confidence intervals. The actual error bars would include errors from models and observational data, and are likely much larger.

not only in the steady state as suggested in Liang et al. (2015) but also in accounting for the temporal variations of vertical heat exchange. Note that $d\overline{H}_d$ is generally smaller than $d\overline{H}_a$ (note the difference in color scale in Fig. 2) and only becomes as important in limited regions, such as near Greenland, Drake Passage, and along the Antarctic Circumpolar Current (ACC).

We examine the global averaged vertical heat fluxes $\langle \overline{H}_v \rangle$ (angle brackets hereinafter represent global horizontal mean) over the two periods as well as their difference $d\langle \overline{H}_v \rangle$ (Figs. 3a–c). Over 1993–2001, almost the entire water column (below 200 m) shows a net upward heat flux of the order of magnitude of 0.1 W m^{-2} . This value is similar to the 20-yr mean results presented in Liang et al. (2015), indicating that the vertical redistribution of heat inside the ocean likely contributed to the observed upper ocean warming before 2001. Over 2002–10, although upward heat flux still dominates the

layer below about 1000 m, there is a net downward heat flux in the upper 200 m. Between 200 and 1000 m, the sign of the vertical heat flux is not significant but does show a negative tendency, indicating a likely change in the global averaged vertical heat flux after 2001.

The difference between $\langle \overline{H}_v \rangle$ over the two periods is displayed in Fig. 3c. Extra downward heat transport with large uncertainty occurred above about 1500 m over 2002–10. Values of $d\langle \overline{H}_v \rangle$ are about $-0.20 \pm 0.24 \text{ W m}^{-2}$ at 200 m, and decrease with increasing depth to about $-0.03 \pm 0.06 \text{ W m}^{-2}$ around 700 m. On the one hand, because the mean warming rate of the upper ocean is determined by the difference between $\langle \overline{Q}_{\text{net}} \rangle$ and $\langle \overline{H}_v \rangle$ through its lower face, the extra downward heat transport could be, at least partially, responsible for the global surface warming slowdown over the 2000s. And this is consistent with the previous inference that the deep ocean received more heat over the 2000s

(e.g., [Chen and Tung 2014](#)). On the other hand, the large uncertainty of $d\langle\overline{H}_v\rangle$ indicates that this extra downward heat transport is not statistically significant, at least for the ocean above 1500 m.

We further separate $d\langle\overline{H}_v\rangle$ into two parts, $d\langle\overline{H}_a\rangle$ and $d\langle\overline{H}_d\rangle$, representing the contributions of ocean advection (including parameterized eddy components) and ocean mixing (both isopycnal and diapycnal mixing, the latter of which includes convective adjustment), respectively ([Figs. 3d,e](#)). Similar to $d\langle\overline{H}_v\rangle$, there is no statistically significant change in the advective vertical heat flux above 1500 m after global integration despite its mostly positive tendency. This again indicates that the global integral of the ocean vertical heat transport involves the summation of positive and negative regional contributions, many of which could be significant and are conventionally considered key. As a consequence, global means/integrals do not necessarily vary in the same way as the key regions. Inferences of global net changes cannot be made from the statistically significant regional changes alone.

In contrast to $d\langle\overline{H}_v\rangle$ and $d\langle\overline{H}_a\rangle$, $d\langle\overline{H}_d\rangle$ is statistically significant and shows an extra downward heat transport above 2000 m over the period 2002–10. Thus over much of the ocean depths, the shifts in ocean vertical heat flux after 2001 are affected not necessarily by the changes in vertical velocity (e.g., [England et al. 2014](#)) but surely by changes in the diffusive heat flux. This surprising observation suggests a potentially important role of ocean mixing processes in explaining the upper ocean heat content change on global and decadal scales. Note that the diffusive vertical heat flux consists of contributions from isopycnal mixing, diapycnal mixing (including convective adjustment), and the three-dimensional temperature gradients [see [Eq. \(1\)](#)]. Preliminary analyses of the changes of the rhs terms in [Eq. \(1\)](#) show that while both terms changed over the 2000s, the extra downward flux is mainly associated with the contribution of isopycnal mixing (rhs1), likely through the changes of the three-dimensional temperature gradients as well as of the projection of isopycnal mixing.

4. Discussion

Many oceanic mechanisms suggested in previous studies are revealed in ECCO v4r1, such as the La Niña-like SST change during the 2000s (e.g., [Meehl et al. 2011](#)) and the associated air–sea heat flux change (e.g., [England et al. 2014](#)), as well as the extra downward heat transport in the North Atlantic ([Chen and Tung 2014](#)). The present analysis shows that although those mechanisms exist in the ocean and are important for changes in regional ocean heat uptake during the 2000s, the global

mean of the change in vertical heat flux is not significantly different from zero in the upper ocean. The nonsignificance of $d\langle\overline{H}_v\rangle$ from ECCO v4r1, a set of ocean state estimates that provide global coverage and regular sampling, both spatially and temporally, raises the question whether an adequate observational database exists to assess changes in the ocean vertical heat flux as well as in the upper ocean heat content over the past few decades.

Of advection and diffusion, the two terms that contribute to the ocean vertical heat transport, advection is more important in determining the spatial pattern of the change in vertical heat flux. However, the global integral of the advective vertical heat flux shows no significant change after 2001. In contrast, the diffusive vertical heat flux, although generally weak regionally (except in the high-latitude regions), when globally integrated exhibits significant extra downward heat transport over the 2000s. This means that ocean mixing, including both isopycnal and diapycnal mixing, is a crucial oceanic mechanism for explaining the recent global surface warming slowdown. Note that the calculation of vertical diffusive heat flux in ECCO v4r1 accounts for not only the isopycnal and diapycnal mixing but also the three-dimensional temperature gradients [[Eq. \(1\)](#)]. Thus, further detailed studies of the contributions of isopycnal and diapycnal mixing, the temporal variation of the diffusive processes and of the background temperature gradients, and their relations with external forcings are needed to better understand the long-term change of ocean heat content and sea surface temperature.

Another observation that deserves attention is the change of importance of different ocean processes on varying temporal and spatial scales. As shown above, although the advective term dominates the regional change of the ocean vertical heat transport, it becomes less important in the global integral. When integrated, many of the large terms of opposite signs cancel out. In contrast, the diffusive processes, which play a less important role regionally, become crucial in the change of the global vertical heat transport. Therefore, for any global integrals, all the oceanic processes, even regionally weak ones, should be assessed carefully. The required accuracy and precision to observe those weak processes is a challenge, highlighting the difficulty in estimating global-mean quantities of climate interest and understanding related physical processes (e.g., [Wunsch 2016](#)).

Revealing similar features to the previous numerical and observational studies supports the existence of the previously proposed oceanic mechanisms, while increasing confidence in the ECCO v4r1 estimate. The existing ocean synthesis products showed great uncertainties in estimating the ocean heat content (e.g.,

Palmer et al. 2017). In the present study, uncertainties are computed only from the spatial and temporal variabilities of the estimates. Because only changes are being discussed, the assumption is made that any systematic model or data errors will be subtractive. Note that because of the lack of enough measurements, the features presented in ECCO v4r1, particularly those in the deep ocean (>2000m), remain uncertain (e.g., Wunsch and Heimbach 2014; Piecuch et al. 2015). Nevertheless, they are from a dynamically and kinematically consistent system that is also largely consistent with the available in situ, satellite, and meteorological data. More observations in the deep ocean are needed to verify and improve the existing estimates, particularly the sign of the ocean vertical heat flux and its changes.

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