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Invited review

A paleo-perspective on ocean heat content: Lessons from the Holocene and Common Era

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ABSTRACT

The ocean constitutes the largest heat reservoir in the Earth's energy budget and thus exerts a major influence on its climate. Instrumental observations show an increase in ocean heat content (OHC) associated with the increase in greenhouse emissions. Here we review proxy records of intermediate water temperatures from sediment cores and corals in the equatorial Pacific and northeastern Atlantic Oceans, spanning 10,000 years beyond the instrumental record. These records suggests that intermediate waters were 1.5–2 °C warmer during the Holocene Thermal Maximum than in the last century. Intermediate water masses cooled by 0.9 °C from the Medieval Climate Anomaly to the Little Ice Age. These changes are significantly larger than the temperature anomalies documented in the instrumental record. The implied large perturbations in OHC and Earth's energy budget are at odds with very small radiative forcing anomalies throughout the Holocene and Common Era. We suggest that even very small radiative perturbations can change the latitudinal temperature gradient and strongly affect prevailing atmospheric wind systems and hence air-sea heat exchange. These dynamic processes provide an efficient mechanism to amplify small changes in insolation into relatively large changes in OHC. Over long time periods the ocean's interior acts like a capacitor and builds up large (positive and negative) heat anomalies that can mitigate or amplify small radiative perturbations as seen in the Holocene trend and Common Era anomalies, respectively. Evidently the ocean's interior is more sensitive to small external forcings than the global surface ocean because of the high sensitivity of heat exchange in the high-latitudes to climate variations.

1. Introduction

The debate about the apparent slow down in the rate of global surface warming during the 1999–2013 decade despite the unabated rise in greenhouse gas (GHG) emissions has brought more attention to the role of the ocean in climate change both among scientists and the general public. The ocean constitutes the largest heat reservoir in the Earth's energy budget due to the high heat capacity of water and large volume and thus plays an important role in mediating the Earth's climate (Levitus et al., 2012). Ongoing research suggests that an increased rate of heat uptake by the ocean's interior may have negated some of the surface warming arguably leading to the apparent slow down in the rate of global warming (e.g., Balmaseda et al., 2013; Levitus et al., 2012; Meehl et al., 2013; Trenberth and Fasullo, 2013), (Fig. 1). Modern estimates of the change in ocean heat content (OHC) go back only to 1955, however the accuracy of the early data sets is debated (https://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/). Since 2006 more accurate estimates have become available from the ARGO array, and they are generally consistent with estimates from the early observations suggesting a relatively constant rate of OHC increase since the early 1990s (Roemmich et al., 2015). A recent compilation suggests that since 1955, ~90% of the excess heat went into the ocean raising concerns about the future state of the oceans (Laffoley and Baxter, 2016). However, given the small magnitude, the brevity of the observed changes in deep OHC and uncertainties of the spatial extent of the current anomalies, any future projection

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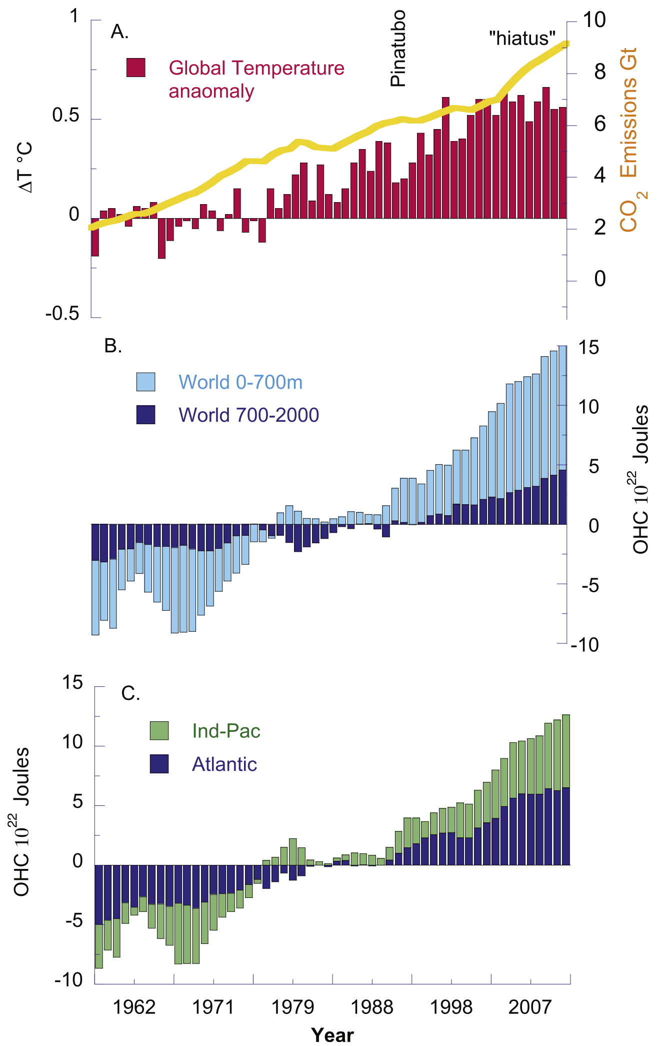

Fig. 1. The last 60 years carbon emissions are shown (A) global surface temperature anomalies are compared with global emissions of CO_2; (B) changes in World Ocean OHC at different depth intervals; (C) changes in OHC at different ocean basins.

depends on our understanding of the mechanisms controlling changes in the ocean's interior heat content.

While ocean heat uptake is directly related to the radiative forcing and climate sensitivity (e.g., Hansen et al., 1984), the rate of heat uptake/release by the ocean is dependent, to a large extent, on dynamic processes controlling air-sea exchange at key locations. The exact nature of these processes is, however, debated. For example, it is still unclear if the largest contribution to the current increase in OHC is due to dynamic changes in the equatorial or the higher latitude oceans.

There is mounting evidence that multiple mechanisms are driving the Pacific Decadal Oscillation (PDO) and that some of these processes are also sensitive and/or related to Pacific OHC (e.g., Balmaseda et al., 2013; England et al., 2014; Meehl et al., 2013; Newman et al., 2016; Thompson et al., 2015; Trenberth and Fasullo, 2013). While the mechanisms controlling the variability of the PDO are still investigated, their global-scale importance is now recognized with the realization that decadal-scale anomalies in surface temperatures, trade winds, sea level pressure and rainfall in the Pacific basin that have developed since the start of the recent hiatus in Earth surface warming (~1999) resemble the negative phase of the PDO (Trenberth and Fasullo, 2013). During this current negative phase of the PDO, the North and South Pacific central gyres and western equatorial Pacific are warmer than average, while the eastern equatorial Pacific is cooler than average (Balmaseda et al., 2013; Meehl et al., 2013; Trenberth and Fasullo, 2013; Trenberth et al., 2014). Recent modeling efforts in conjunction with analysis of ARGO float data indicate elevated heat storage in the Pacific water column during this most recent negative phase of the PDO (Balmaseda et al., 2013; England et al., 2014; Kosaka and Xie, 2013; Meehl et al., 2013; Roemmich et al., 2015; Trenberth and Fasullo, 2013) supporting the arguments that the tropical and mid-latitude regions of the Pacific Ocean are important sites of heat exchange between the ocean and the atmosphere. In the subtropics of the Pacific and Atlantic, surface waters can seasonally descend away from the surface along isopycnal surfaces to sub-thermocline depths and flow towards the equator. This process is referred to as the shallow meridional overturning cell. An unprecedented strengthening of the Pacific Ocean shallow overturning cells related to trade wind strengthening has been suggested as the primary cause of the enhanced oceanic heat gain via this subtropical route (Balmaseda et al., 2013; England et al., 2014; Trenberth and Fasullo, 2013). Stronger trade winds coupled with changes in ocean circulation associated with the PDO phase switch in 1999–2000 have resulted in a cooling of the equatorial surface ocean over the last 15 years (England et al., 2014; Trenberth and Fasullo, 2013).

Equatorial processes mainly affect the heat content of the thermocline and may also affect the upper water column (0–700 m). However, a significant amount of warming (~30%) is observed at intermediate ocean depths (Balmaseda et al., 2013; Roemmich et al., 2015). This warming has arguably been attributed to high latitude processes both in the North Atlantic and the Southern Ocean. Based on the reanalysis of hydrographic data collected since 1970 it has been argued that a large part of the recent increase in OHC, particularly below 1000 m, occurred in the Atlantic. Accordingly, the heat gain may be due to the enhancement of the Atlantic Meriodional Overtruning Circulation (AMOC) in response to the recurrent salinity anomaly in the subpolar North Atlantic (Balmaseda et al., 2013; Chen and Tung, 2014). Accordingly, the recovery from the great salinity anomaly of the mid 20th century (Curry et al., 2003), led to the increase in surface density, which would have enhanced vertical convection in the Labrador Sea and subpolar region leading to greater sequestration of heat and CO_2. This observation-based hypothesis is consistent with model results suggesting that variations in the strength and depth of the AMOC plays a key role in transporting and redistributing thermal energy to depth, thus regulating the heat capacity of the ocean in response to climate change (Kostov et al., 2014).

An alternative, though not a mutually exclusive explanation, attributes the global increase in OHC at intermediate depths (~700–1400 m) to greater heat gain from surface ocean-atmospheric interactions in the Southern Ocean (Roemmich et al., 2007, 2015). The greater heat gain in the Southern Ocean could be partly caused by the faster warming rate of the Southern vs. Northern Hemisphere high latitudes and the greater area of the Southern Ocean. However, it has been proposed that the strengthening of the Southern Westerly Winds (SWW) and resultant spin up of the subtropical gyres, played a more important role in enhancing the heat gain in the southern high latitudes. The strengthening and poleward shift of the SWW occurred in response to a positive Southern Annular Mode since ~1970 (Thompson et al., 2011). The poleward shift of the SWW enhances the large-scale upwelling in the Southern Ocean due to Ekman divergence south of the Polar Front (~50°S), thus bringing deep colder water to the surface, which in turn promotes heat and gas uptake from the atmosphere. Continuous upwelling and relatively quick northward transport of the cold waters at the surface limits the surface