

World Ocean Heat Content and Thermosteric Sea Level change (0-2000 m), 1955-2010

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We provide updated estimates of the change of ocean heat content and the thermosteric component of sea level change of the 0-700 and 0-2000 m layers of the World Ocean for 1955-2010. Our estimates are based on historical data not previously available, additional modern data, and bathythermograph data corrected for instrumental biases. We have also used Argo data corrected by the Argo DAC if available and used uncorrected Argo data if no corrections were available at the time we downloaded the Argo data. The heat content of the World Ocean for the 0-2000 m layer increased by $24.0 \pm 1.9 \times 10^{22}$ J (± 2 S.E.) corresponding to a rate of 0.39 W m^{-2} (per unit area of the World Ocean) and a volume mean warming of 0.09° C . This warming corresponds to a rate of 0.27 W m^{-2} per unit area of earth's surface. The heat content of the World Ocean for the 0-700 m layer increased by $16.7 \pm 1.6 \times 10^{22}$ J (2S.E.) corresponding to a rate of 0.27 W m^{-2} (per unit area of the World Ocean) and a volume mean warming of 0.18° C . The

World Ocean accounts for approximately 93 % of the warming of the earth system that has occurred since 1955. The 700-2000 m ocean layer accounted for approximately one-third of the warming of the 0-2000 m layer of the World Ocean. The thermosteric component of sea level trend was $0.54 \pm 0.05 \text{ mm yr}^{-1}$ for the 0-2000 m layer and $0.41 \pm 0.04 \text{ mm yr}^{-1}$ for the 0-700 m layer of the World Ocean for 1955-2010.

1. Introduction

We have previously reported estimates of the variability of ocean heat content (OHC) of the World Ocean to a depth of 3000 m [Levitus *et al.*, 2000]. Here we present estimates for the upper 2000 m of the World Ocean with additional historical and modern data [Levitus *et al.*, 2005a,b; Boyer *et al.*, 2009] using running pentadal (5-year) temperature analyses [Levitus *et al.*, 2000]. A lack of high-quality CTD and reversing thermometer data at depths exceeding 2000 m in recent years precludes us from producing recent analyses for deeper depths.

We use the term “ocean heat content” as opposed to “ocean heat content anomaly” used by some authors because “ocean heat content” is an anomaly by definition. OHC is always computed with a reference mean subtracted out from each temperature observation. Otherwise the OHC computation depends on the temperature scale used.

The importance of the variability of the total heat content of the world ocean can hardly be underestimated. Levitus *et al.* [2001] documented quantitatively that global ocean heat

content is the major term in earth's heat balance.

2. Data and Method

We use data from the World Ocean Database 2009 [Boyer *et al.* , 2009] plus additional data processed through the end of 2010 (www.nodc.noaa.gov).

Argo profiling float data that have been corrected for systematic errors provide data through a nominal depth of 1750-2000 for the post-2004 period on a near-global basis. We have used data that were available as of January 2011. Many of these data have been corrected by the Argo delayed-mode quality control teams. If Argo data have not been corrected at the time we downloaded these data we still used them. Unlike salinity data from profiling floats, temperature data do not appear to have significant drift problems associated with them. It is our understanding that problems with profiling floats identified by *Barker et al.* [2011] have for the most part been corrected. Also, we believe that our quality control procedures (*Boyer et al.* [2009]; *Levitus and Boyer* [1994]) have eliminated most remaining egregious problems. Typically most Argo floats in our present database reach a maximum observed depth of 1970 m. Thus, these profiles only extend down to the 1750 m standard depth level of our analyses. Our temperature anomaly fields could be considered to be more representative of the 0-1750 m layer of the World Ocean however we have compared the OHC1750 and OHC2000 and find no difference between them. We hope to acquire additional deep ocean data from research cruises so we have opted to present results for the 0-2000 m layer.

We apply corrections for instrumental offsets of expendable bathythermographs (XBT) and mechanical bathythermographs (MBT) found by *Gouretski and Koltermann* [2007] as described by *Levitus et al.* [2009]. XBT profiles are excluded from our computations if they lack the metadata needed to correct drop rates. This is approximately 50 % of all XBT profiles that we have in the World Ocean Database

From every observed one-degree mean temperature value at every standard depth level we subtract off a climatological value. For this purpose we use the monthly climatological fields of temperature from *Locarnini et al.* [2010]. Then we composite all anomaly values in each one-degree square by five-year running compositing periods. Next the same objective analysis procedure used by *Locarnini et al.* [2010] is applied to these gridded, composited anomaly values and a global, gridded field with temperature anomaly values defined in every one-degree square is produced for each standard depth level. To compute heat content at each gridpoint the specific heat and density were computed using annual climatological values of temperature and salinity from *Locarnini et al.* [2010] and *Antonov et al.* [2010]. We use a first-guess field of zero for our anomaly field computations. This is a conservative but we think appropriate procedure given the lack of data in some regions and some time periods. There are alternative methods for interpolation or as some investigators refer to it “infilling”. For example *Gille* [2008] used a basin or global mean trend in data void areas. *Domingues et al.* [2008] used basis functions of near-global sea level determined from satellite altimeter data for 1993-2006 and historical observations of the steric component of sea level to

derive near global ocean heat content fields. Each of these methods has deficiencies. For example the basis functions used by *Domingues et al.* [2008] may be changing with time. We computed decadal monthly means by averaging all data within each month for decadal periods beginning with 1955-1964 and then averaging these decadal climatological monthly means to compute the long-term climatological monthly mean (1955-2006) at each gridpoint. This is necessary in particular because of the large amount of Argo profiling float data introduced to the observing system in recent years which can bias climatologies to the Argo sampling period. This change made no difference in the time series of northern hemisphere ocean heat content but did make a small difference in the southern hemisphere ocean heat content trend.

3. Global and basin OHC estimates

Figure 1 shows the 0-2000 m and 700-2000 m OHC pentadal time series for the World Ocean. We will denote the OHC integrated to a particular depth as OHCXXXX in which “XXXX” is the maximum depth of vertical integration in meters. The global linear trend of OHC2000 is $0.43 \times 10^{22} \text{ J yr}^{-1}$ for 1955-2010 which corresponds to a total increase in heat content of $24.0 \pm 1.9 \times 10^{22} \text{ J}$ ($\pm 2\text{S.E.}$), and a mean increase of temperature of 0.09°C . This represents a rate of 0.39 W m^{-2} per unit area of the World Ocean and a rate of 0.27 W m^{-2} per unit area of the earth’s surface. The corresponding total OHC700 increase for the same period is $16.7 \pm 1.6 \times 10^{22} \text{ J}$ (2S.E.) J that represents a rate of 0.27 W m^{-2} per unit area of the World Ocean. The linear trends account for 93 and 91 per cent of the variability of the OHC2000 and OHC700 World Ocean time series respectively. The

standard error of the mean (S.E.) for each pentadal estimate is computed as described in the Appendix in the Supplemental Material of this paper. T Figure 1 shows that the 700-2000 m layer is responsible for approximately one third of the total warming of the 0-2000 m layer. The blue bar chart at the bottom represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used to compute one-degree square values at 700 m depth. The blue line is the same quantity as for the bar chart but for 2000 m depth. Supplemental Figure S1 displays OHC2000 estimates for each major ocean basin. Figure S2 is similar to Figure S1 but shows the OHC700 time series.

Figure 2 shows the linear trend and total increase of heat content for 1955-2010 of global and basin heat content as a function of depth (0-2000 m) for 100 m layers. We computed basin time series of OHC for 100 m-thick layers from 0 to 1500 m and 250 m-thick layers between 1500 m and 2000 m. Then the linear trends for each time series were computed. For the deepest two layers (1500-1750 m and 1750-2000 m) we added the linear trends of 1500-1750 m and 1750-2000 m layers to get the total change of the 1500-2000 m layer and divided that total change by five (the number of 100 m-thick layers between 1500 m and 2000 m) to plot in Figure 2. Warming is surface intensified in all basins. In the 0-100 m layer the Pacific exhibits the largest total increase. Below the 100 m layer the Atlantic exhibits the largest increase of all ocean basins at all layers down to 2000 m depth. Figure S3 shows the percent variance accounted for by the linear trend in each layer of the basins in Figure 2. In the Atlantic Ocean the linear trend has accounted for at least 60 % of the variance at all layers to depths just exceeding 1500 m. The Pacific shows percent

variance contributions near or exceeding 60 % in the 0-100 m layer and between 500 and 1100 m depth. The Indian Ocean differs considerably and shows the greatest percent variance contributed by the linear trend in the 0-100 m, 200-500 m, and 1100-1500 m layers.

4. Zonally-integrated OHC pentadal difference estimates and trends

Figure 3 shows the linear trend of the zonally integrated OHC2000 fields for the 1955-2010 period as a function of latitude for the World Ocean and individual ocean basins. At nearly every latitude the World Ocean has warmed. Relative extrema in the linear trend of OHC occur at several latitudes in each basin. Some of these extremes coincide between the three basins and others do not. Figure S4 shows the percent variance accounted for by the linear trends shown in Figure 3. Generally the percent variance accounted for is relatively high in the vicinity of the extrema observed in Figure 3. In the Atlantic the percent variance exceeds 60% at nearly all latitudes between 50°S and 40°N and exceeds 80% in much of this region.

Figure S5 shows the zonally integrated OHC700 and OHC2000 difference fields for the (2006-2010) minus (1955-1959) pentads as a function of latitude. As indicated by Figure 3, warming is nearly ubiquitous at all latitudes. In addition heat has been stored in the 700-2000 m layer. Previous evidence of the role played by the 700-2000 m layer in storing heat particularly in the southern hemisphere was given by *Levitus et al.* [2005a] and *Cai et al.* [2010]. *Cai et al.* used ensemble mean results from seventeen AOGCMs

(Atmosphere-Ocean General Circulation Models) that were forced by the increase of atmospheric greenhouse gases (from the Third Coupled Model Intercomparison Project (CMIP3) in support of the IPCC AR4). They found relatively “fast, deep ocean warming in the midlatitude” band of the southern hemisphere which agrees with our observational results. Furthermore they found that “Counterintuitively, the net heat required for warming in this midlatitude band is largely derived from surface heat fluxes south of 50°S, where the changes are an order of magnitude greater than that over the 35°-50°S midlatitude band”.

5. Global distribution of ocean heat storage

We define ocean heat storage as the time derivative of OHC. Supplemental Figure S6 shows the linear trend of global geographical distribution of heat storage for the 0-2000 m layer for 1955-2010. Heat storage is generally positive as would be expected from Figure 3. A notable exception is the subarctic gyre of the North Atlantic Ocean. This is due to multidecadal variability in ocean temperature anomalies that we have observed in this region. *Hatún et al.* [2005] noted that the subarctic Atlantic Ocean began warming in 1995 after a period of cooling that began in the 1970s. We will document these changes in more detail in a manuscript in preparation. Figure S7 shows the percent variance accounted for by the linear trend shown in Figure S6. The 0-700 m global ocean heat storage is given in Figure S8 and the percent variance account for by the trend is given by Figure S9. Supplemental Tables S1 and S2 provide ocean heat content estimates and calculation discussed in this paper in tabular form.

6. Contributions to ocean heat content from regions deeper than 2000 m depth

Although observational data are relatively sparse from depths exceeding 2000 m in the World Ocean, several recent studies have appeared that estimate the change in ocean heat content in this layer. *Purkey and Johnson* [2010] quantified abyssal global and deep Southern Ocean temperature trends between the 1990s and 2000s with CTD data from research cruises. *Kouketsu et al.* [2011] assimilated temperature and salinity data into an ocean general circulation model (OGCM) and found a global increase of 0.8×10^{22} J decade⁻¹ for depths exceeding 3000 m for the 1990s to 2000s. *Kawano et al.* [2010] estimated that for the Pacific Ocean the increase in ocean “heat content below 3000 m was about 5% of the ocean-wide increase” between 1999 and 2007.

7. Thermosteric sea level

We update our earlier estimates of the thermosteric component of global sea level rise (TCSL) [*Antonov et al.*, 2005]. For 1955-2010 the TCSL has increased at rates of 0.54 mm yr⁻¹ and 0.41 mm yr⁻¹ for the 0-2000 m and 0-700 m layers respectively. The 0-700 m value is approximately 25 % larger than our earlier estimate which most likely can be attributed to additional data now available for use in this study. The global and basin time series of TCSL are shown in supplementary Figures S10 (0-2000 m) and S11 (0-700 m). Supplement Table S3 provides TCSL rates in tabular form.

For comparison we note that a total global sea level rise of approximately 1.6-1.8 mm yr⁻¹ had been estimated on the basis of tide gauge data for most of the twentieth century. More recently there has been acceleration in sea level rise and both tide gauges and satellite altimetry estimate a rise of sea level of approximately 3.1 mm yr⁻¹ since 1991.

8. Discussion

One important result presented here is that each major ocean basin has warmed at nearly all latitudes. A net warming has occurred despite interannual to decadal variability of the ocean associated with phenomenon such as the El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the North Atlantic Oscillation as well as other such phenomenon. The fact that relative extremes of OHC are a function of latitude and in some cases are at different latitudes in each major ocean basin indicates different ocean, or ocean-atmosphere, responses to the common forcing of the observed increase in greenhouse gases in earth's atmosphere occurred. Although carbon dioxide is well-mixed in the atmosphere, the response of earth's climate system to increasing atmospheric greenhouse gases is not simple [Cai *et al.*, 2010]. Work by Lee *et al.* [2011] documents interbasin exchange of heat that is of possible relevance to both internal and anthropogenic variability of the world ocean.

Using model simulations based on AOGCM simulations, Dommenget [2009] concluded that “continental warming due to anthropogenic forcing (e. g., the warming at

the end of the last century or future climate change scenarios) is mostly (80%-90%) indirectly forced by the contemporaneous ocean warming, not directly by local radiative forcing.” Thus even if greenhouse gas emissions were halted today than regardless of the residence time of the carbon dioxide in today’s atmosphere, the ocean would continue to heat the atmosphere [Wetherald *et al.*, 2001] .

One feature of our results is that the previous multidecadal increase in OHC700 that we have reported [Levitus *et al.*, 2009] (updated estimates available online at www.nodc.noaa.gov) leveled off during the past several years. This leveling is not as pronounced in our OHC2000 estimates indicating that heat is being stored in the 700-2000 m layer as we have shown here. We also note that our new yearly OHC2000 time series (not shown here) indicate that the positive trend in this quantity continues through 2011 although with interannual and interseasonal variability apparent.

We emphasize that despite the surface intensification of the observed ocean warming, subsurface layers make a substantial contribution to the increase in OHC. Heat may have been stored at ocean depths exceeding 2000 m during the observational period we are studying and may be of significance for earth’s heat balance. We simply do not have enough in situ CTD or reversing thermometer data from depths exceeding 2000 m available to ascertain if there is a contribution from this layer. If the results of Kouketsu *et al.* [2011] are correct, this would mean a contribution of 1.6×10^{22} J from the ocean region in the 3000 m-bottom layer. However a reduction of global ocean heat storage may result from the increase of sulfur in earth’s atmosphere due to increased burning of coal as well

as decreased solar radiation and changes in the state of ENSO as recently suggested by *Kaufmann et al.* [2011]. Observed changes in stratospheric water vapor [*Solomon et al.*, 2010] and stratospheric aerosols [*Solomon et al.*, 2011] may also have contributed. *Church et al.* [2011] have discussed these factors in a study of the variability of ocean heat content and sea level.

We have estimated an increase of 24×10^{22} J representing a volume mean warming of 0.09° C of the 0-2000 m layer of the World Ocean. If this heat were instantly transferred to the lower 10 km of the global atmosphere it would result in a volume mean warming of this atmospheric layer by approximately 36° C (65° F). This transfer of course will not happen; earth's climate system simply does not work like this. But this computation does provide a perspective on the amount of heating that the earth system has undergone since 1955.

All data and pentadal analyses used in this study as well as the yearly and seasonal gridded heat content fields are freely available at (<http://www.nodc.noaa.gov/OC5/indprod.html>). This is in accordance with IPCC, ICSU, IOC, and national data policies of many countries.

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NODC for data processing work and our colleagues at the NODC Ocean Climate Laboratory for their work in constructing the *World Ocean Database* which made this work possible. We appreciate review of our manuscript by Charles Sun and anonymous reviewers. The Argo profiling float data used in this study were made freely available by the International Argo Project and the national initiatives that contribute to it (<http://www.argo.net>). Argo is a pilot programme of the Global Ocean Observing System. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

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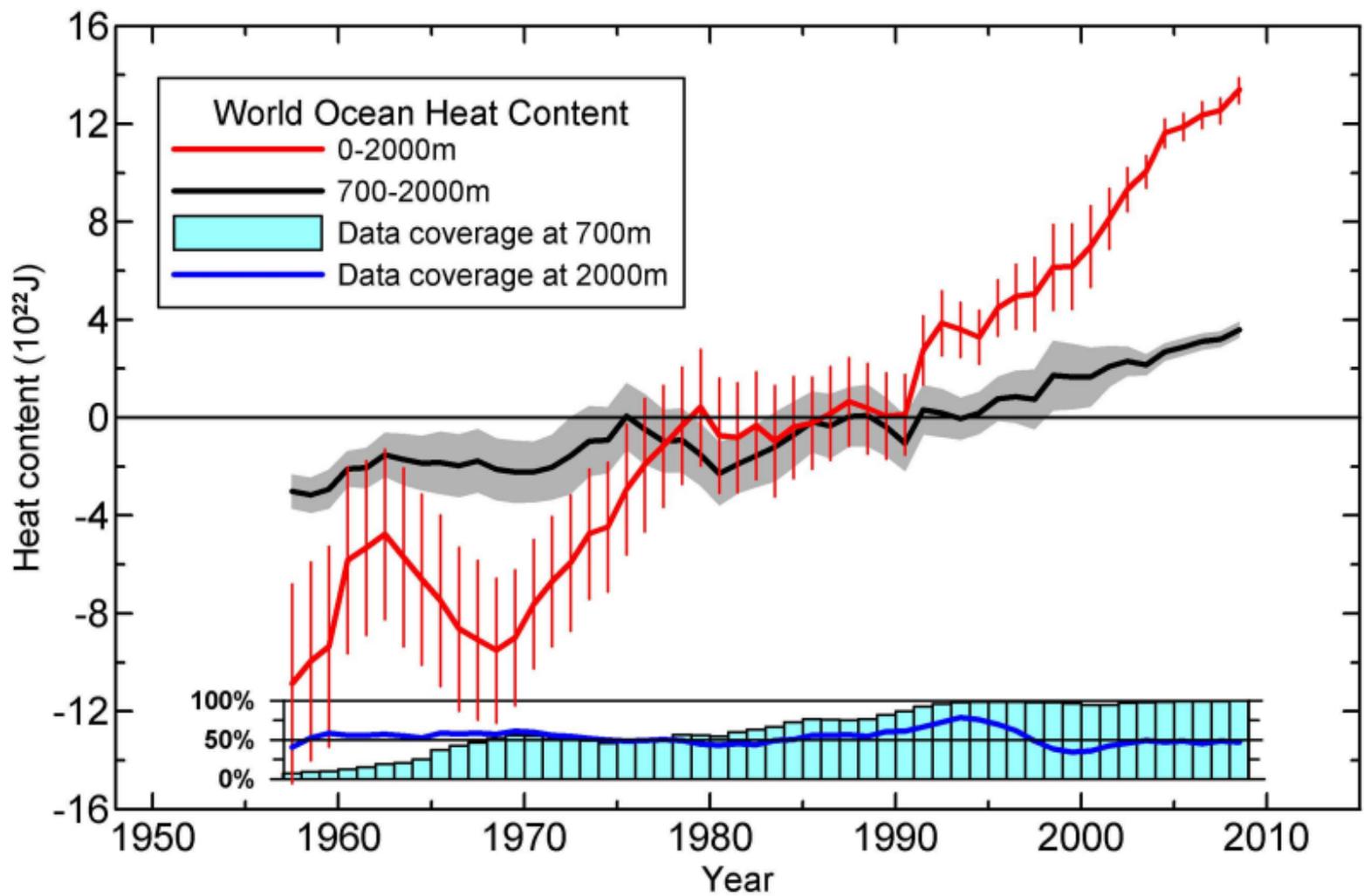
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FIGURE CAPTIONS:

Figure 1. Time series for the World Ocean of ocean heat content (10^{22} J) for the 0-2000 m (red) and 700-2000 m (black) layers based on running pentadal (five-year) analyses. Reference period is 1955-2006. Each pentadal estimate is plotted at the midpoint of the 5-year period. The vertical bars represent ± 2 *S.E. about the pentadal estimate for the 0-2000 m estimates and the grey-shaded area represent ± 2 *S.E. about the pentadal estimate for the 0-700 m estimates. The blue bar chart at the bottom represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used in their computation at 700 m depth. Blue line is the same as for the bar chart but for 2000 m depth.

Figure 2. Linear trend and total increase of ocean basin heat content based on the linear trend of global and individual basins as a function of depth (0-2000 m) for 100 m thick layers.

Figure 3. Linear trend (10^{18} J yr⁻¹) (1955-1959) to (2006-2010) in zonally integrated ocean heat content for the World Ocean and individual ocean basins as function of latitude for the 0-2000 m layer. Red indicates a positive trend and blue a negative trend.



Ocean heat content change (10^{22} J)

