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Recent cooling of the upper ocean

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[1] We observe a net loss of 3.2 (±1.1) × 10^{22} J of heat from the upper ocean between 2003 and 2005. Using a broad array of in situ ocean measurements, we present annual estimates of global upper-ocean heat content anomaly from 1993 through 2005. Including the recent downturn, the average warming rate for the entire 13-year period is 0.33 ± 0.23 W/m^2 (of the Earth's total surface area). A new estimate of sampling error in the heat content record suggests that both the recent and previous global cooling events are significant and unlikely to be artifacts of inadequate ocean sampling. **Citation:** Lyman, J. M., J. K. Willis, and G. C. Johnson (2006), Recent cooling of the upper ocean, *Geophys. Res. Lett.*, *33*, L18604, doi:10.1029/2006GL027033.

1. Introduction

[2] With over 1000 times the heat capacity of the atmosphere, the World Ocean is the largest repository for changes in global heat content [*Levitus et al.*, 2005]. Monitoring ocean heat content is therefore fundamental to detecting and understanding changes in the Earth's heat balance. Past estimates of the global integral of ocean heat content anomaly (OHCA) indicate an increase of 14.5 × 10^{22} J from 1955 to 1998 from the surface to 3000 m [*Levitus et al.*, 2005] and 9.2 (±1.3) × 10^{22} J from 1993 to 2003 in the upper (0 – 750 m) ocean [*Willis et al.*, 2004]. These increases provide strong evidence of global warming. Climate models exhibit similar rates of ocean warming, but only when forced by anthropogenic influences [*Gregory et al.*, 2004; *Barnett et al.*, 2005; *Church et al.*, 2005; *Hansen et al.*, 2005].

[3] While there has been a general increase in the global integral of OHCA during the last half century, there have also been substantial decadal fluctuations, including a short period of rapid cooling (6 × 10^{22} J of heat lost in the 0–700 m layer) from 1980 to 1983 [*Levitus et al.*, 2005]. Most climate models, however, do not contain unforced decadal variability of this magnitude [*Gregory et al.*, 2004; *Barnett et al.*, 2005, their Figure S1; *Church et al.*, 2005; *Hansen et al.*, 2005] and it has been suggested that such fluctuations in the observational record may be due to inadequate sampling of ocean temperatures [*Gregory et al.*, 2004]. We have detected a new cooling event that began in 2003 and is comparable in magnitude to the one in the early 1980s. Using high-resolution satellite data to estimate sampling error, we find that both the recent event and the cooling of the early 1980s are significant with respect to these errors.

2. Heat Content Anomaly

[4] Using a broad array of in situ temperature data from expendable bathythermographs (XBTs), ship board conductivity-temperature-depth (CTD) sensors, moored buoy thermistor records (primarily from Tropical Atmosphere Ocean array), and autonomous profiling CTD floats (primarily from Argo) the global integral of OHCA of the upper 750 m is estimated from the start of 1993 through the end of 2005 (Figure 1). The global integral is computed from 1/4 degree mapped fields of annual averaged OHCA as in the work of *Willis et al.* [2004], except that in the present analysis the altimeter data are not used. From 1993 to 2003, the heat content of the upper ocean increased by 8.1 (±1.4) × 10^{22} J. This increase was followed by a decrease of 3.2 (±1.1) × 10^{22} J between 2003 and 2005. The decrease represents a substantial loss of heat over a 2-year period, amounting to about one fifth of the long-term upper-ocean heat gain between 1955 and 2003 reported by *Levitus et al.* [2005].

[5] From 1993 to 2005, the average rate of upper-ocean warming as determined by a linear least squares fit is 0.33 ± 0.23 W/m^2 (of the Earth's total surface area). This convention is chosen to emphasize the observationally supported relationship between ocean heat content and the Earth's energy balance [*Pielke*, 2003; *Levitus et al.*, 2005; *Wong et al.*, 2006]. The uncertainty represents the 95% confidence interval and reflects both the random error in each annual estimate as well as the interannual variability in the curve that is not explained by a linear trend. To calculate the uncertainty, the effective degrees of freedom were computed by dividing the length of the time series by the decorrelation length scale of the residuals from the fit. The recent decrease in heat content amounts to an average cooling rate of −1.0 ± 0.3 W/m^2 (of the Earth's total surface area) from 2003 to 2005, and results in a lower estimate of average warming from 1993 to 2005 than that recently reported for the 1993 to 2003 period [*Willis et al.*, 2004]. It is important to note that this decrease causes greater uncertainty in the long-term warming rate because the cooling reflects interannual variability that is not well represented by a linear trend. This cooling event, as well as the cooling in the early 1980s, illustrates the importance of accounting for interannual variability when determining long-term rates of ocean warming. This interannual variability complicates the task of detecting upper ocean warming due to anthropogenic influence, which is assumed to have a time scale of many decades.

[6] The recent downturn in OHCA roughly coincides with the spin up of Argo (www.argo.net) in 2002. Argo

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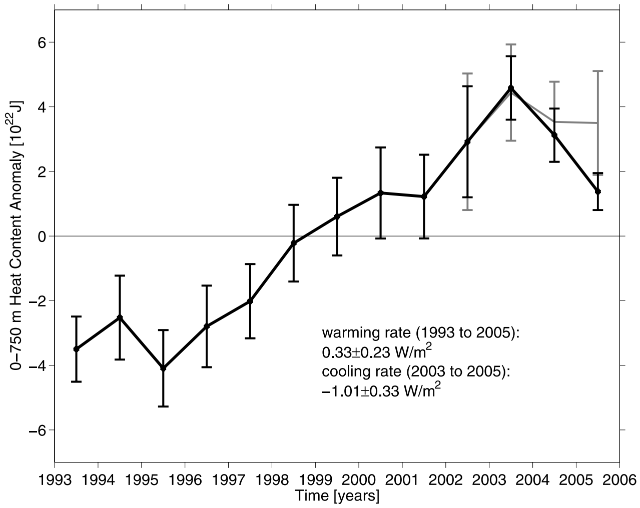

Figure 1. Globally averaged annual OHCA (10^{22} J) in the upper 750 m estimated using in situ data alone from 1993 through 2005 (black line) and using in situ data excluding profiling floats (gray line). Error bars (from Figure 3) reflect the standard error estimates discussed in Section 3. Linear trends are computed from a weighted least square fit [*Wunsch*, 1996] and reflect the OHCA estimate made using all available profile data. Errors for inset linear trend estimates are quoted at the 95% confidence interval.

has dramatically improved sampling and introduced a large amount of data from new instruments, namely autonomous profiling CTD floats. In order to test for potential biases due to this change in the observing system, globally averaged OHCA was also computed without profiling float data (Figure 1, gray line). The cooling event persisted with removal of all Argo data from the OHCA estimate, albeit more weakly and with much larger error bars. This result suggests that the cooling event is real and not related to any potential bias introduced by the large changes in the characteristics of the ocean observing system during the advent of the Argo Project. Estimates of OHCA made using only data from profiling floats (not shown) also yielded a recent cooling of similar magnitude.

[7] The relatively small magnitude of the globally averaged signal is dwarfed by much larger regional variations in OHCA (Figure 2). These variations sometimes exceed the equivalent of a local air-sea heat flux anomaly of 50 W/m^2 applied continuously over 2 years and so are too large to be caused by this mechanism alone. Changes such as these are also due to mesoscale eddy advection, advection of heat by large-scale currents, and interannual to decadal shifts in gyre circulation that are associated with climate phenomena such as El Niño [*Johnson et al.*, 2000], the North Atlantic Oscillation [*Curry and McCartney*, 2001], the Pacific Decadal Oscillation [*Deser et al.*, 1999], and the Antarctic Oscillation [*Roemmich et al.*, 2006]. Owing in part to the strength of these advection-driven changes, the source of the recent globally averaged cooling (Figure 1) cannot be localized from OHCA data alone.

3. Uncertainty in the Global Integral

[8] Assessing the significance of the comparatively tiny (order 1 W/m^2) changes in the global average OHCA requires an estimate of how well the large regional signals are resolved by the often sparsely sampled in situ OHCA data. Since late 1992, dense, high-quality measurements of sea surface height anomaly (SSHA) have been obtained via satellite altimeter. Maps of SSHA from Aviso (a combined satellite altimeter product) contain variability on scales as small as ten days and 150 – 200 km [*Ducet et al.*, 2000], have almost complete global coverage (excluding ice-covered regions), and are related to ocean heat content [*White and Tai*, 1995; *Gilson et al.*, 1998; *Willis et al.*, 2004]. Admittedly, SSHA variability is not perfectly correlated with OHCA variability. SSHA variations are also influenced by ocean freshwater content owing to precipitation, evaporation, and run-off, as well as by deep ocean

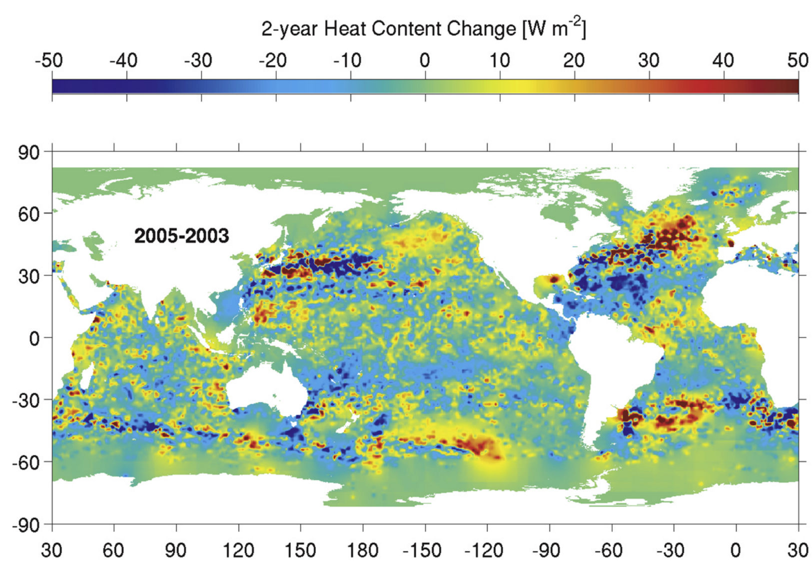

Figure 2. Map of OHCA change (W m^{-2}) in the upper 750 m from 2003 to 2005.

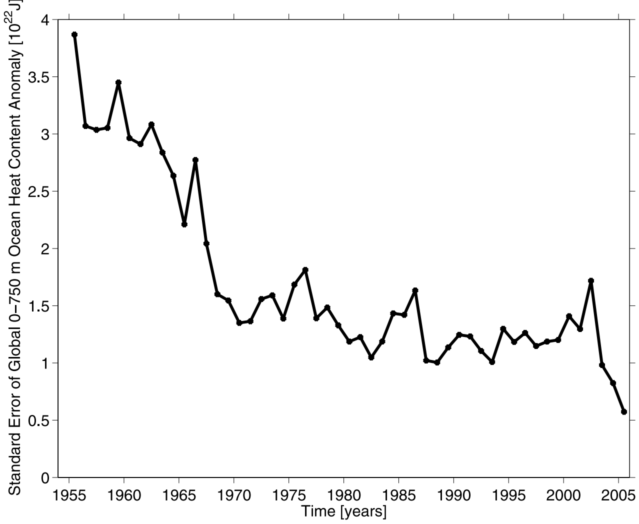

Figure 3. Standard error for globally averaged OHCA (10^{22} J) of the upper 750 m from 1955 through 2005. This quantity was estimated using satellite altimeter data maps and the historical sampling patterns for in situ profile data in each year as discussed in the text.

variations (below 750 m in this case). Despite these complicating factors, the correlation between SSHA and OHCA holds reasonably well and is used here to compute the uncertainty in the in situ estimate of OHCA.

[9] Estimates of the uncertainty in OHCA are made for the years 1955 to 2005 by sub-sampling the 13-year record of SSHA in the same manner as the in situ sampling pattern for a given year, N. The global integral of SSHA, for the 13-year record, is constructed from maps made from the sub-sampled data set [*Willis et al.*, 2004] and compared to the global integral of SSHA based on the complete maps of Aviso data. Taking the time series based on the complete maps as truth, the uncertainty for year N is expressed as a standard deviation:

$$sampling\_error(N) = 5.1 \times 10^{22} J \cdot cm^{-1} \left[\frac{\sum_{i=1993}^{2005} [SSH_{total}(i) - SSH_{sub\_N}(i)]^2}{13} \right]^{1/2} \quad (1)$$

where the proportionality constant between SSHA and OHCA is 5.1×10^{22} J $\cdot$ cm^{-1} [*Willis et al.*, 2004], SSH_{total} is the global average of SSHA from the complete maps for year i, and SSH_{sub_N} is the global average of SSHA from the Aviso data for year i sub-sampled at observation locations for year N and then remapped. There is only one realization of the globally averaged OHCA each year, therefore the standard deviation of the sampling error and the standard error are the same.

[10] This method most likely underestimates the sampling error, as the 13-year record of SSHA is missing variability from time scales longer than decadal and shorter than 10 days. The method also assumes that the shorter time scale variability in the decades preceding the 1990s is similar to that from 1993 to 2005, which may not be true. Hence, the error estimate is probably most accurate for the period of satellite altimetry, since 1993. Despite these caveats, this process likely produces a reasonable estimate of the sampling error in one-year averages of OHCA prior to 1993 as well. It is worth noting, however, that lack of a longer altimeter record may preclude using this technique to determine accurate uncertainties for the long-term warming rate reported by *Levitus et al.* [2005] that has been the subject of recent debate [*Gregory et al.*, 2004; S. Gille, Decadal-scale temperature trends in the Southern Hemisphere, manuscript in preparation, 2006].

[11] The standard error on the annually averaged global mean from Aviso SSH maps [*Willis et al.*, 2004] is 0.2×10^{22} J. This term is combined with the standard error from the sampling error computed above, assuming these two errors are independent, to yield the standard error on the OHCA estimate (Figure 3) for a given year N:

$$standard\_error\_OHCA(N) = \left[\left(0.2 \times 10^{22} \mathrm{J}\right)^2 + sampling\_error(N)^2 \right]^{1/2}. \quad (2)$$

[12] The time-period from 1955 to 2005 can be broken into three different epochs with regards to in situ sampling of OHCA. The first epoch, prior to the advent of XBTs, ended around 1967. Globally averaged uncertainty during this epoch (Figure 3) is on the same order as the decadal signal [*Levitus et al.*, 2005] making it difficult to quantify decadal changes in the globally averaged OCHA prior to 1968.

[13] Upon the commencement of widespread use of XBTs in 1968, a second epoch began that continued until 2002. Uncertainty in globally averaged OHCA drops by a factor of six from 1955 to 1968 (Figure 3). The decrease in uncertainty is due to the increase in the number of observations from 4,500 in 1955 to 31,900 in 1968, an increase that was fueled by the introduction of the XBT. During the second epoch, the error decreases only slightly with time (Figure 3) but is generally small compared to decadal changes in globally averaged OHCA. In particular, the 6×10^{22} J decrease in heat content during the early 1980s that was reported by *Levitus et al.* [2005] lies well outside the range of uncertainty presented here.

[14] A third epoch began around 2003 with the ramp-up of Argo. The goal of this international project is to deploy and maintain an array of 3000 autonomous profiling CTD floats designed to accurately measure temperature and salinity in the upper 2000 m of the global ice-free ocean at 10-day intervals and $3^\circ \times 3^\circ$ spatial resolution. From 2002 to 2005 there was a factor of three decrease in the standard error of OHCA that resulted directly from Argo data. The uncertainty in the global average of annual OHCA is now at a historic low of 0.6×10^{22} J. Thus, the magnitude of the recent cooling is also well outside the range of uncertainty. While the number of in situ samples is about the same in 2002 and 2005, the latter year is sampled by well-dispersed Argo floats and has a much more even distribution of data compared to 2002 (auxiliary material

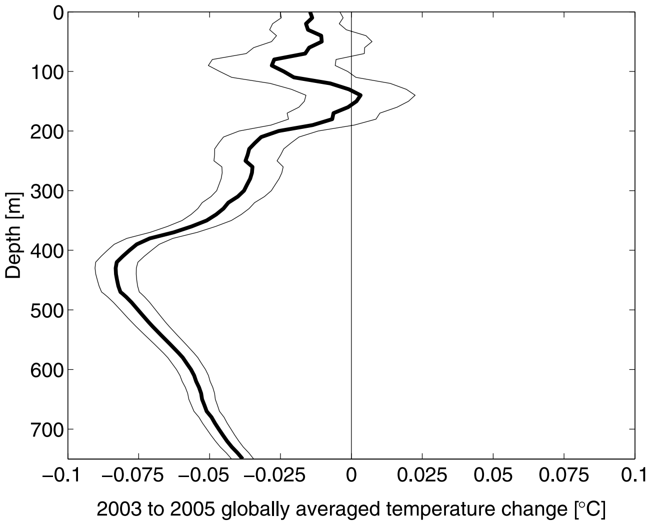

Figure 4. Globally averaged ocean temperature change (°C) from 2003 to 2005 versus depth (m). Thin black lines represent error bounds determined by scaling the uncertainty in heat content using regression coefficients [*Willis et al.*, 2004].

Figure S1[1]). In addition, because Argo floats report back in real time, near real-time estimates of OHCA are now possible.

4. Vertical Structure of Cooling

[15] The depth structure of globally averaged temperature change between 2003 and 2005 (Figure 4) allows a few more insights into the recent cooling. Uncertainty in the temperature change was computed by scaling the 1×10^{22} J standard error in the heat content decrease using regression coefficients for temperature variability [*Willis et al.*, 2004]. The average uncertainty is about 0.01°C at a given depth. The cooling signal is distributed over the water column with most depths experiencing some cooling. A small amount of cooling is observed at the surface, although much less than the cooling at depth. This result of surface cooling from 2003 to 2005 is consistent with global SST products (e.g. http://www.jisao.washington.edu/data_sets/global_sstanomts/). The maximum cooling occurs at about 400 m and substantial cooling is still observed at 750 m. This pattern reflects the complicated superposition of regional warming and cooling patterns with different depth dependence, as well as the influence of ocean circulation changes and the associated heave of the thermocline.

[16] The cooling signal is still strong at 750 m and appears to extend deeper (Figure 4). Indeed, preliminary estimates of 0 – 1400 m OHCA based on Argo data (not shown) show that additional cooling occurred between depths of 750 m and 1400 m. As the Argo target sampling depth of 2000 m is achieved by an increasing number of floats, the array will better resolve future deeper changes in OHCA. Variations of pentadal global integrals of OHCA to 3000 m are similar in size and magnitude to annual 0–700 m estimates [*Levitus et al.*, 2005], suggesting that most of the interannual warming and cooling signals are found in the upper 700 m. Still, deepening of the warm bowls in subtropical gyres [*Roemmich et al.*, 2006] and/or the warming of bottom water formed in high latitudes [*Østerhus and Gammelsrød*, 1999; *Johnson and Doney*, 2006] could partially offset the upper ocean cooling. It seems unlikely, however, that the entire signal could be compensated by these processes over such a short period of time.

[17] Assuming that the 3.2 (±1.1) $\times 10^{22}$ J was not transported to the deep ocean, previous work suggests that the scale of the heat loss is too large to be stored in any single component of the Earth's climate system [*Levitus et al.*, 2005]. A likely source of the cooling is a small net imbalance in the 340 W/m^2 of radiation that the Earth exchanges with space. Imbalances in the radiation budget of order 1 W/m^2 have been shown to occur on these time scales and have been related to changes in upper OHCA [*Wong et al.*, 2006]. These findings suggest that the observed decrease in upper ocean heat content from 2003 to 2005 could be the result of a net loss of heat from the Earth to space. Nevertheless, further work will be necessary to determine the exact cause of the cooling.

5. Discussion

[18] This work has several implications. First, the updated time series of ocean heat content presented here (Figure 1) and the newly estimated confidence limits (Figure 3) support the significance of previously reported large interannual variability in globally integrated upper-ocean heat content [*Levitus et al.*, 2005]. However, the physical causes for this type of variability are not yet well understood. Furthermore, this variability is not adequately simulated in the current generation of coupled climate models used to study the impact of anthropogenic influences on climate [*Gregory et al.*, 2004; *Barnett et al.*, 2005; *Church et al.*, 2005; *Hansen et al.*, 2005]. Although these models do simulate the long-term rates of ocean warming, this lack of interannual variability represents a shortcoming that may complicate detection and attribution of human-induced climate influences.

[19] Changes in OHCA also affect sea level. Sea level rise has a broad range of implications for climate science as well as considerable socioeconomic impacts [*Intergovernmental Panel on Climate Change*, 2001]. Diagnosing the causes of past and present sea level change and closure of the sea level budget is therefore a critical component of understanding past changes in sea level as well as projecting future changes. The recent cooling of the upper ocean implies a decrease in the thermosteric component of sea level. Estimates of total sea level [*Leuliette et al.*, 2004] (available at http://sealevel.colorado.edu), however, show continued sea-level rise during the past 3 years. This suggests that other contributions to sea-level rise, such as melting of land-bound ice, have accelerated. This inference is consistent with recent estimates of ice mass loss in Antarctica [*Velicogna and Wahr*, 2006] and accelerating ice mass loss on Greenland [*Rignot and Kanagaratnam*, 2006] but closure of the global sea level budget cannot yet be achieved. New satellite observations from the Gravity Recovery and Climate Experiment (GRACE; launched in March, 2002 and administered by NASA and Deutsches

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL027033.

Zentrum für Luft-und Raumfahrt, GRACE will map Earth's gravity field approximately once every 30 days during its lifetime) should soon provide sufficient observations of the redistribution of water mass to more fully describe the causes of recent sea-level change.

[20] Finally, the estimates presented here are made possible only by recent improvements in the global ocean observing system. The sharp decrease in the error since 2002 is due to the dramatic improvement of in situ sampling provided by the Argo array of autonomous profiling CTD floats, and the real-time reporting of Argo data made it possible to extend the estimate through 2005. Characterization of the error budget, which is of paramount importance in the estimate of such globally averaged quantities, was made feasible by the long-term maintenance of high quality altimeter missions such as TOPEX/Poseidon and Jason. The issues relating to sea level rise and the global water budget can only be addressed when the record of satellite gravity measurement from GRACE achieves adequate duration. GRACE, Argo, and satellite altimetry are core components of the global ocean observing system. Failure to maintain any one of these observing systems would seriously impair our ability to monitor the World Ocean and to unravel its importance to the climate system.

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