Development of Global Heat and Freshwater Anomaly Analyses

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Project Summary:

Understanding global climate variability requires knowledge of ocean temperature and salinity fields (or more precisely ocean heat and fresh water content). Accurate estimates of changes in distribution of ocean heat and fresh water content combined with an analysis of how thermohaline (temperature-salinity) anomalies enter, circulate within, and leave the ocean is necessary to monitor and understand interannual to decadal changes in climate. Such fields and analyses help to verify climate models and improve their predictive skill. They help to diagnose the components of sea level change (ocean temperature variations versus ocean mass variations).

This project is developing, updating, and analyzing global analyses of ocean temperature and salinity using quality-controlled compilations of in situ temperature and salinity data from eXpendable Bathy Thermographs (XBTs), shipboard Conductivity-Temperature-Depth (CTD) measurements, CTD-equipped autonomous profiling floats (Argo), moored buoys, and other sources. These data are used to estimate global ocean temperature and salinity fields, hence ocean heat and freshwater content variations on annual time-scales. Historically, in situ data distributions can relatively sparse, especially before the advent of Argo. However, variations in ocean heat content are closely related to variations ocean sea-surface height, which has been very well measured since late 1992 by satellite altimeters. By exploiting this close relationship, we are able to quantify the errors inherent in estimating a global average of upper ocean heat content from an incomplete data set. We can also exploit the relationship to improve maps of ocean heat content from in situ data by using the altimeter data with local correlation coefficients applied as a first guess at upper ocean heat content in poorly measured regions.

This project, a part of the NOAA Office of Climate Observations Ocean Observing System Team of Experts, by providing analyses of ocean data, will help NOAA to use and assess the effectiveness of the sustained ocean observing system for climate. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory by the PMEL and JIMAR investigator, but in very close consultation with the co-investigator at NASA's Jet Propulsion Laboratory.

Project Accomplishments:

In FY2006 we have updated maps of annual upper (0-750 m) ocean heat content primarily for the ice-free portions of the globe from 1993 through 2005 in two manners. For one set of maps we used in situ temperature profile data alone the better to investigate large (basin) spatial scale and long (decadal) time-scale variability. For the other estimate we combined in-situ and satellite altimetric data (following Willis et al. 2004) to better resolve smaller (sub-gyre) scale spatial variability over shorter (year-to-year) time-scales.

Comparing the in situ data distribution for 2005 vs. 1994 (Figure 1 top panel) shows the effect of the growing Argo array, with over twice the number of data for 2005 compared with 1994, and a much more even geographical (and temporal) coverage in 2005 compared with 1994. Since the start of the Argo Program in 2000, the number of in situ observations has steadily ramped up (Figure 1 bottom panel). When the Argo array is at full strength, it alone should deliver about 100,000 temperature profiles per year.

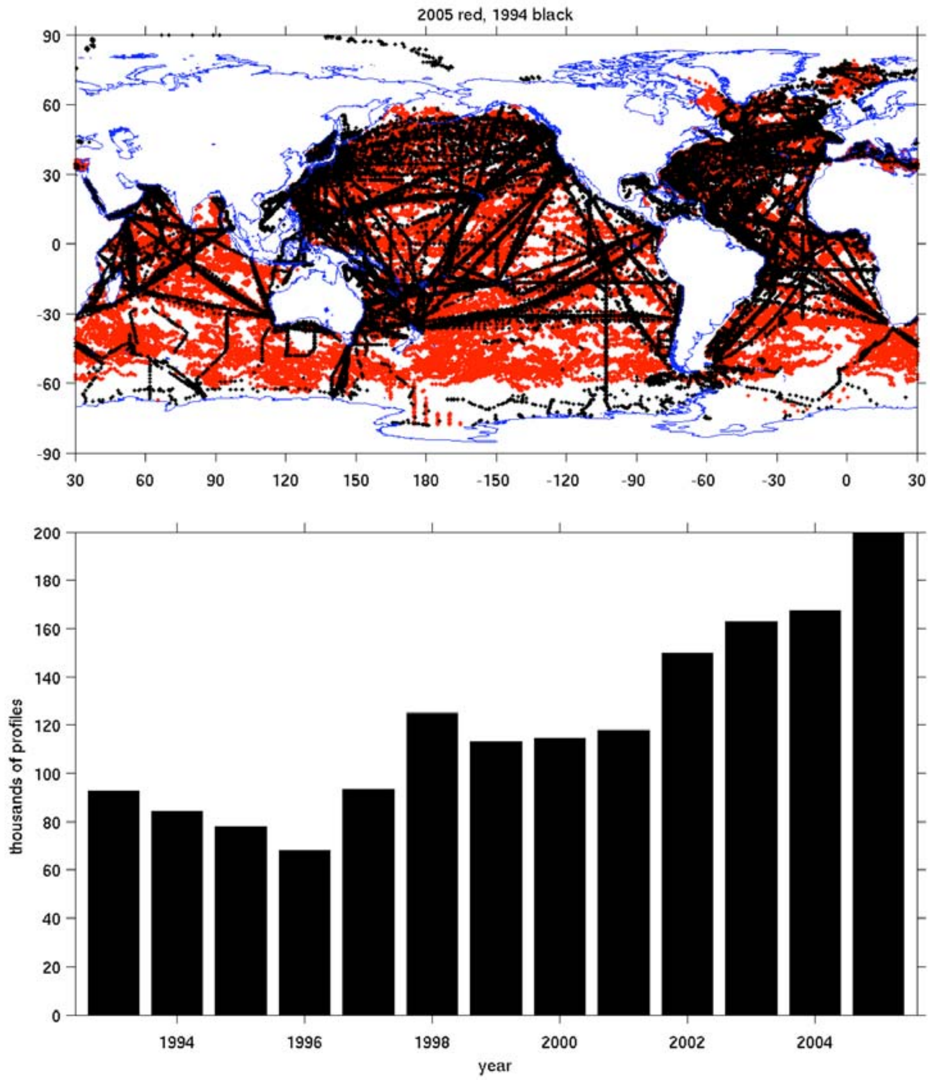

Figure 1. Location of in situ temperature profiles from 2005 (red dots) with 1994 profile locations (black dots) overlaid (top panel). Number of in situ temperature profiles per year (bottom panel).

The difference between 2004 and 2003 upper ocean heat storage (Figure 2, top panel) and that between 2005 and 2004 (Figure 2, bottom panel) demonstrate the large year-to-year variability in ocean heat storage, with changes reaching or exceeding the equivalent of a 80 W m^{-2} magnitude surface flux over a year in many places. Ocean advection likely plays a large role in many of these changes. For instance, the increase in equatorial Pacific Ocean upper ocean heat content in 2004 compared to 2003, and then subsequent decrease in 2005 compared to 2004, is due to shifts in ocean currents (as well as air-sea heat flux changes) associated with El Niño. The large changes in both years associated with the western boundary currents and the Antarctic Circumpolar Current are likely partially due to advection as well.

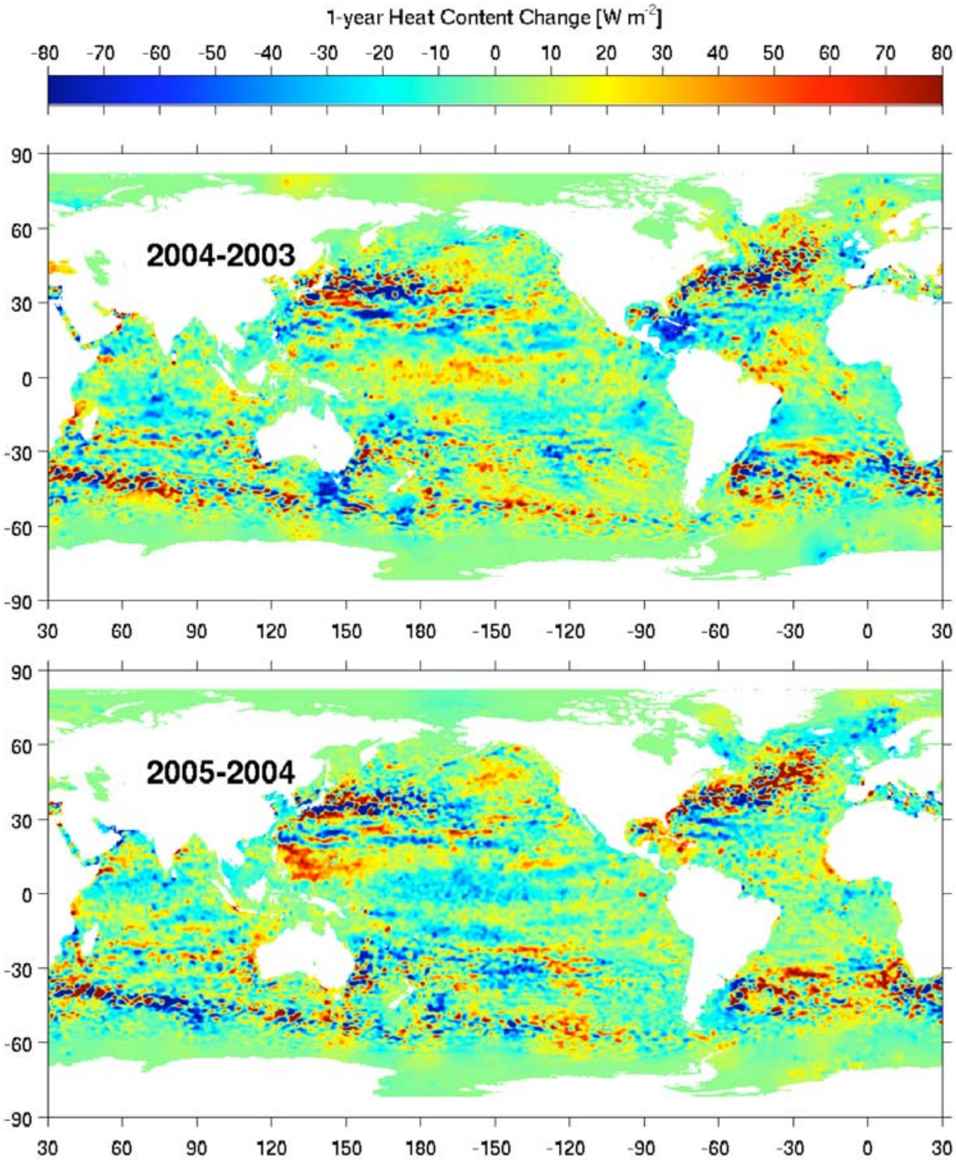

Figure 2. Upper (0 - 750 m) ocean heat content anomaly changes from the 1-year average for 2004 with that for 2003 subtracted (top panel) and from the 2005 average with that for 2004 subtracted (bottom panel) expressed as a surface flux [W m^{-2}] over the intervening years. Maps are made from the combination of in situ heat content anomalies and satellite altimeter data following Willis et al. (2004).

Local linear trends in upper ocean heat storage estimated over the entire 13-year period analyzed (Figure 3, top panel) generally have larger spatial scales but smaller amplitudes than the year-to-year changes. Examination of the ratio of the trend to the 95% uncertainty in the trend (Figure 3, bottom panel) shows that the trend is significant only in limited regions. The large positive values in the northern North Atlantic Ocean may be due in part to the mid 1990's shift in the North Atlantic Oscillation. The large negative values in the subpolar North Pacific may partly reflect changes in the Pacific Decadal Oscillation. The Southwest Pacific also contains significant positive values, including south of Australia, in the Tasman Sea, and east of New Zealand.

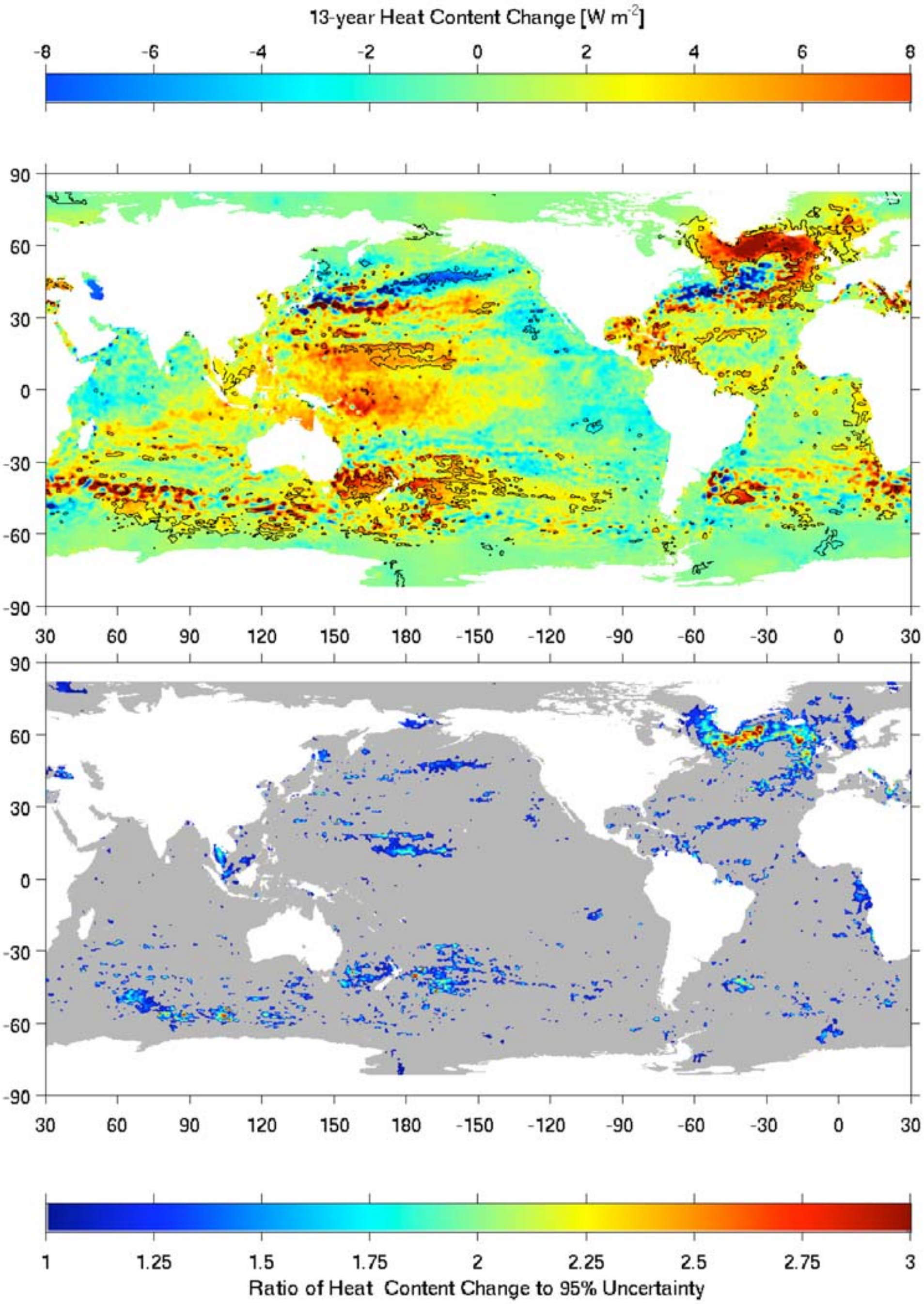

Figure 3. Linear estimates of upper (0 – 750 m) ocean heat content change from 1993 to 2005 (top panel) with areas of significant slope outlined in black as estimated by the ratio of these trends to their 95% uncertainty estimates (bottom panel, where colored regions are significantly different from zero but grey are not). Heat content estimates used here are based on a combination of in situ heat content anomalies and satellite altimeter data following Willis et al. (2004).

Globally integrated upper ocean annual heat content anomalies based on in situ data alone (Figure 4) yield an even smaller trend of 0.59 (±0.14) W m^{-2} (at the 95%

confidence level) over the analysis period. This number is expressed as a flux over the entire surface of the earth.

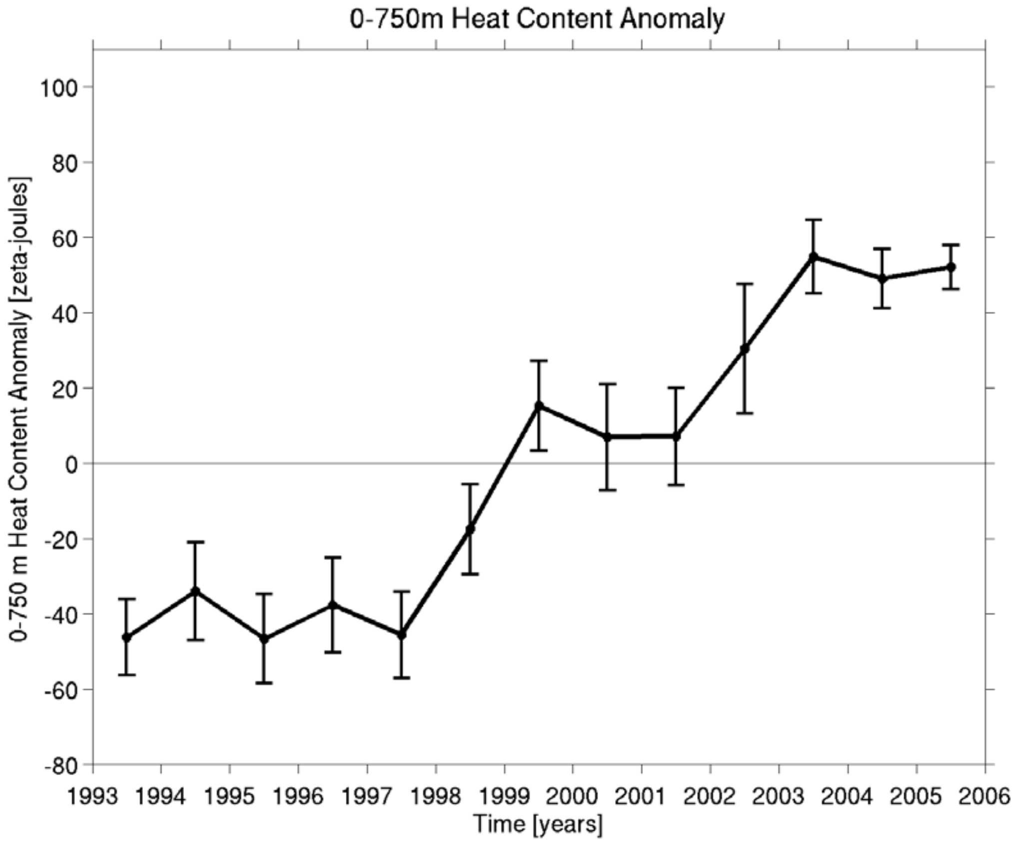

Figure 4. Globally averaged interannual heat content anomalies using maps from in situ data alone. Sampling standard errors are displayed (bars). Instrument biases could increase uncertainties over those shown here.

To quantify the effect of improved in situ ocean heat content measurements over time as the Argo array grows, we interpolated each year (from 1993 through 2005) of synthetic heat anomalies generated from the altimeter data following Willis et al., (2004) to the locations and time of year of in situ observation locations for a given year. We then used these interpolated values as fake "in situ" data to construct heat anomaly maps using the Willis et al. (2004) methodology from 1993 through 2005 and a given year's sampling pattern. For a given year's sampling pattern, we then compared each of the 13 mapped fields to the fully resolved synthetic fields. This yielded a variance from which an error estimate could be derived. We combined this error estimate with an appropriately scaled estimate of the RMS error in globally averaged sea level about a 1-year mean (0.2×10^{22} J) following Willis et al. (2004). We assume the two error sources are independent (Figure 5).

The sampling standard errors in Figure 4 vary significantly from year to year (Figure 5). Most notably, as the Argo array grew dramatically in from 2003 through 2005 with more widespread sampling than previous years (see. Figure 1), the sampling standard errors shrank significantly compared with the previous years (Figure 5). There may still be a lag of several years for in situ data to makes its way to the archives we are using, in which case sampling standard errors for subsequent analyses that include additional in situ data will be further reduced.

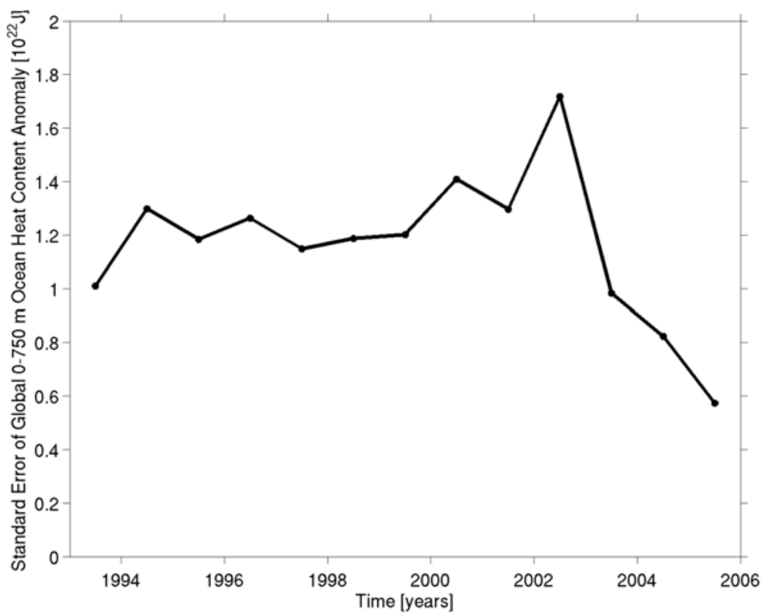

Figure 5. Sampling standard errors of global upper ocean heat content anomalies following Lyman et al. (2006).

Some of our analyses have been published in the Bulletin of the American Meteorological Society as part of the supplement "State of the Climate in 2005" report (Johnson et al., 2006). The global averaged in situ data based upper ocean heat content and error estimates were not ready for that report but were recently published elsewhere (Lyman et al. 2006). This paper generated significant scientific and media interest. In addition, we recently built project web page (http://oceans.pmel.noaa.gov/).

Revision Notes, 19 April 2007:

After this report was first submitted but before it went to press two instrument errors in the data used in ocean heat content estimates were discovered. These discoveries prompted revisions to Figures 2-4 and some of the text in this report. We have also just submitted a correction to Lyman et al. (2006) for publication as a result of these discoveries. One error is a large cold bias in a small fraction of Argo float data. Ascribing incorrect pressures to otherwise valid temperature and salinity data caused this error. The other error is a smaller but more prevalent warm bias in eXpendable BathyThermograph (XBT) data. This error may result from variations in fall rates and it may vary with time, manufacturer, and other variables. The erroneous Argo float data will eventually be corrected, but for now they have simply been removed from the analyses presented here. The XBT biases will require substantial investigation for optimal correction. For the results presented here a very preliminary ad-hoc time-independent reduction of the XBT depths by a factor of 0.985 after application of the latest recommended fall rate corrections has been used to reduce temperature discrepancies between the XBT data and data from other sources (including floats).

FY2006 Publications and Reports:

Aagaard, K., T. J. Weingartner, S. L. Danielson, R. A. Woodgate, G. C. Johnson, and T. E. Whitledge. 2006. Some controls on flow and salinity in Bering Strait. *Geophysical Research Letters*, **33**, L19602, doi:10.1029/2006GL026612.

Johnson, G. C. 2006. Generation and initial evolution of a mode water θ-S anomaly. *Journal of Physical Oceanography*, **36**, 739-751.

Johnson, G. C., J. M. Lyman, and J. K. Willis, 2006: Global Oceans: Heat Content. *In* State of the Climate in 2005, K.A. Shein, Ed., *Bulletin of the American Meteorological Society*, **87**, *6*, S23-S24.

Johnson, G. C., J. M. Toole, and N. G. Larson, 2006. Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *Journal of Atmospheric and Oceanic Technology*, accepted.

Lyman, J. M., G. C. Johnson, and W. S. Kessler. 2006. Distinct 17-day and 33-day tropical instability waves in subsurface observations. *Journal of Physical Oceanography*, in press.

Lyman, J. M., J. K. Willis, and G. C. Johnson. 2006. Recent cooling of the upper ocean. *Geophysical Research Letters*, **33**, L18604, doi:10.1029/2006GL027033.