Uncertainties in thermosteric sea level estimates

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Abstract

ARGO hydrographic profiles have vastly improved the sampling of temperature and salinity in the global oceans, in particular by providing relatively frequent observations in regions with a sparse climate record (e.g. the Southern Ocean). When compared with satellite altimetry and ocean mass estimates from GRACE, these observations can, in principle, can provide a nearly complete picture of recent sea level change.

Hydrographic observations demonstrate an apparent cooling of the ocean since 2002, which would imply up to a 2 mm drop in thermosteric sea level. We present the recent Jason altimetry observations of total sea level and GRACE measurement of ocean mass. We have sampled the altimetric observations at the times and locations of the ARGO profiles and have developed an error estimate for the hydrographic observations of heat storage.

In an analysis of the World Ocean Database (WOD), Antonov et al. [2005] reported a linear trend of 0.33 ± 0.04 mm/year in thermosteric sea level for the global (50°S - 65°N, 0-700 m) oceans during the period 1955-2003 and a trend of 1.23 ± 0.20 mm/year during 1993-2003. Miller and Douglas [2004] have suggested that smoothing errors in high variability regions such as the Gulf Stream can bias thermosteric estimates. Gregory et al. [2004] have demonstrated that gaps in the observational record can have a significant effect on the estimated global trend.

1. Introduction

Lyman et al. [2006] estimate the uncertainty in ocean heat content (Figure 1) by sub-sampling the 13-year record of sea level in the same manner as the in situ hydrographic sampling pattern for a given year. They compare the global integral of sea level from maps constructed from a sub-sampled data set to the global integral of the complete sea level data set [Willis et al., 2004]. Taking the time series based on the complete maps as truth, the uncertainty for each year is expressed as a standard deviation:

$$\text{sampling\_error(year)} = 5.1\times10^{22}\ \text{J cm}^{-1}\left[\frac{\sum_{i=1993}^{2005} SSH_{global} - SSH_{sub\_year}(i)}{13}\right]^{1/2}$$

where SSH_{total} is the global average of sea surface height from the complete maps for year i, and SSH_{sub_year} is the global average of sea surface height from the data for year i sub-sampled at observation locations for each year and then remapped.

Willis et al. [2004] estimated that the standard error on the annually averaged global mean sea level from weekly SSH maps is 0.2 x 10^{22} J. Combining this standard error with the sampling error computed yields the standard error on the ocean heat content estimates for each year (Figure 2):

$$\text{standard\_error(year)} = \left[\left(0.2\times10^{22}\,\text{J}\right)^2 + \text{sampling\_error(year)}^2\right]^{1/2}$$

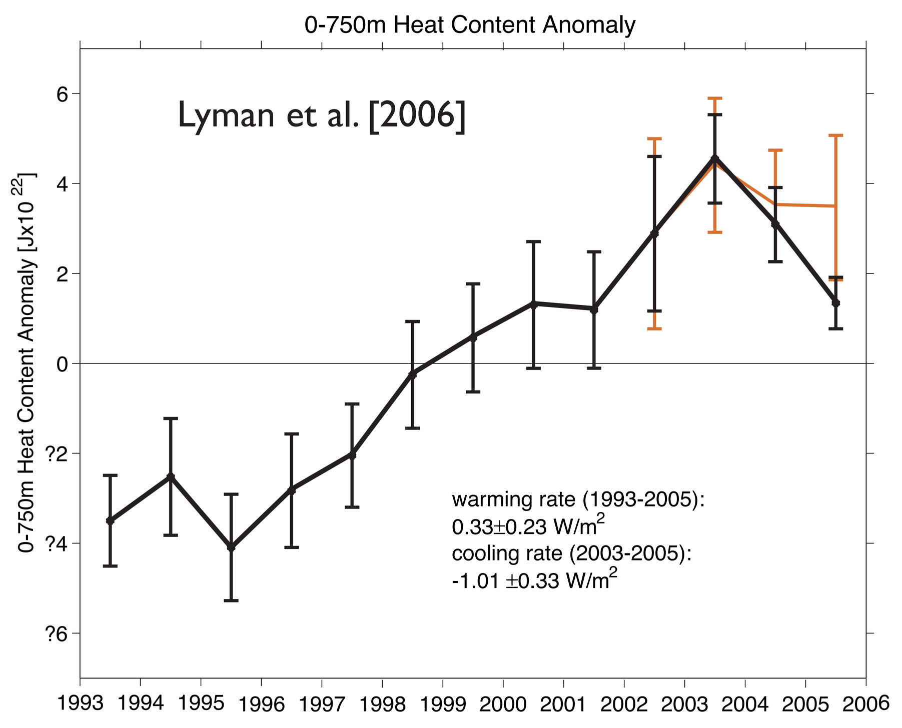

Figure 1. Globally-averaged ocean heat content anomaly in the upper 750 m from in situ data alone (black line) and from in situ data excluding profiling floats (red line).

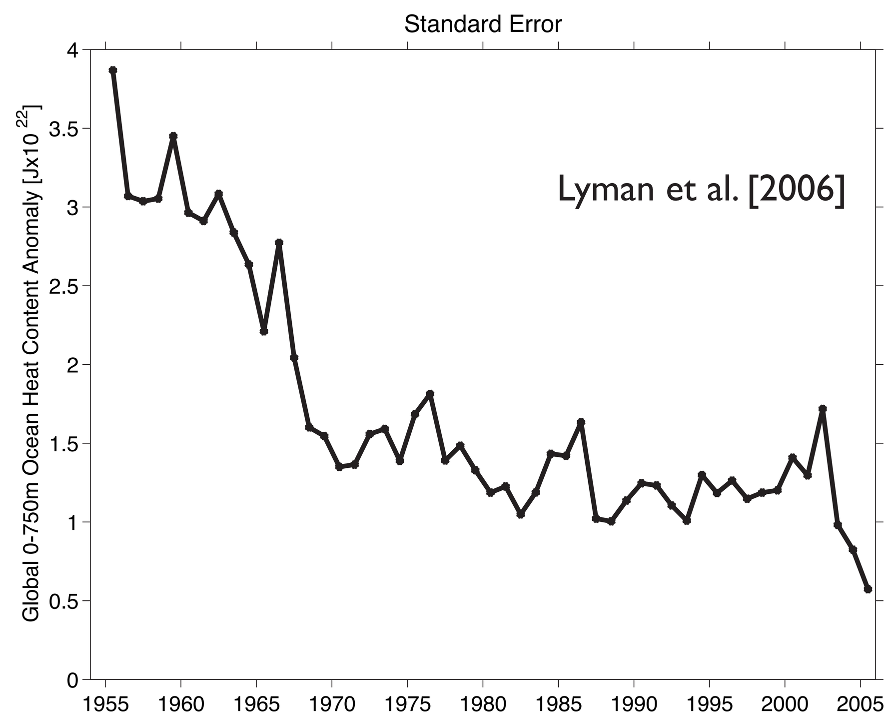

Figure 2. Standard error for globally averaged ocean heat content anomaly of the upper 750 m. Lyman et al. [2006] computed this quantity using sea surface height maps from altimeter data and the historical sampling patterns for in situ profile data.

2. Sea surface height maps

The historically sparse sampling of in situ ocean profiles suggests that large regional signals could be undersampled to an extent that biases the calculation of the global mean. To estimate the errors, we adopt an approach similar to Lyman et al. [2006] and sample observed sea level variations as a proxy to assess the significance of variations in global average ocean heat content. Since late 1992, highly accurate sea level anomaly (SLA) measurements have been obtained from up to four simultaneously orbiting satellite altimeters. SLA variability is strongly, but not perfectly, correlated with ocean heat variability. SLA variations are also influenced by ocean mass fluxes including precipitation, evaporation, and run-off, as well as by deep ocean currents.

A combined satellite altimeter product produced by Aviso provides near-global weekly maps of SLA at resolutions of 1/3° and 1/4° (see Figure 3). These maps capture variability on scales as small as 150–200 km [Ducet et al., 2000].

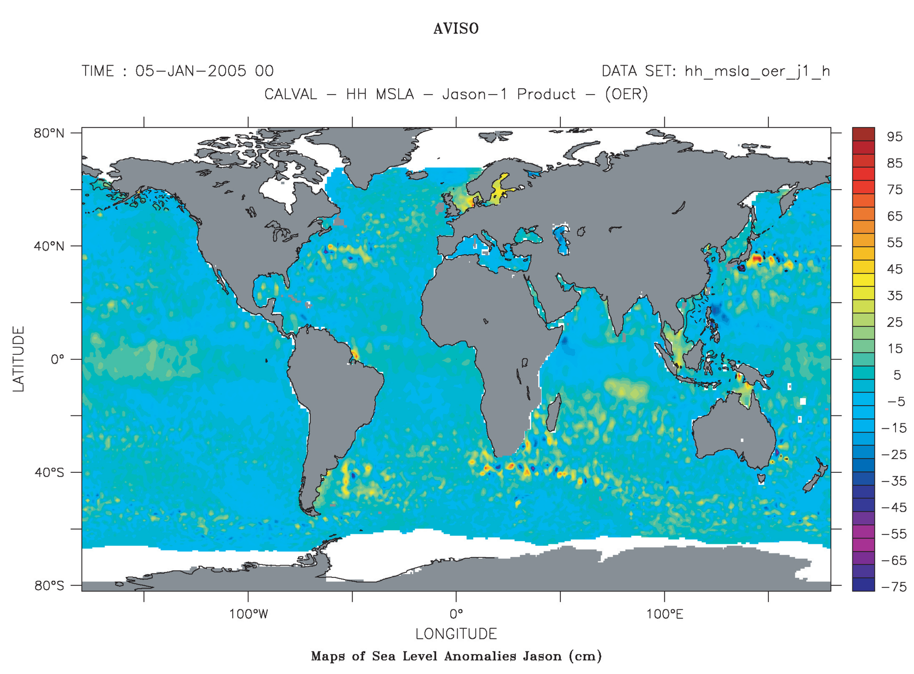

Figure 3. Aviso sea level anomaly map for 5 January 2005.

3. Hydrographic profile coverage

Sampling of hydrographic data increased significantly beginning in 1968 with the introduction of XBTs and increased further with the deployment of Argo floats starting around 2003 (Figure 4). The goal of Argo is to deploy and maintain an array of 3000 autonomous profiling 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°x3° spatial resolution. The current network (Figure 5) greatly supplements the spatial extent of the previous coverage (Figure 6), though the Southern Ocean lags (Figure 7).

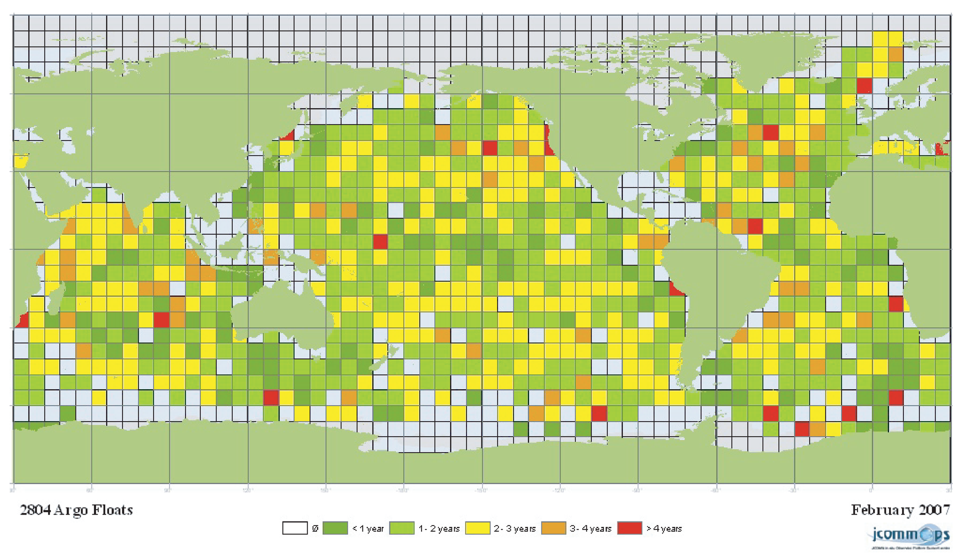

Figure 4. Argo network age.

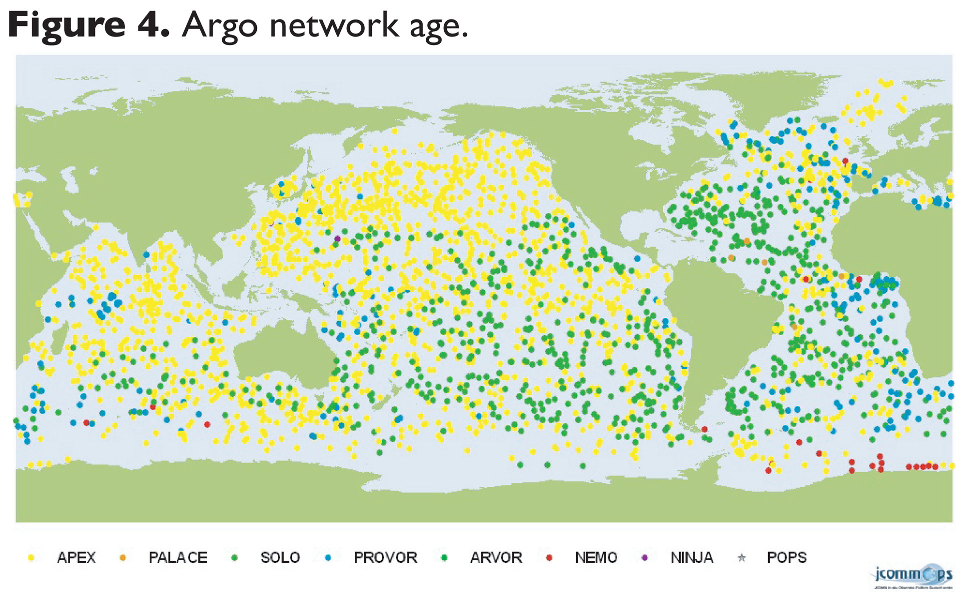

Figure 5. Argo network on 27 February 2007.

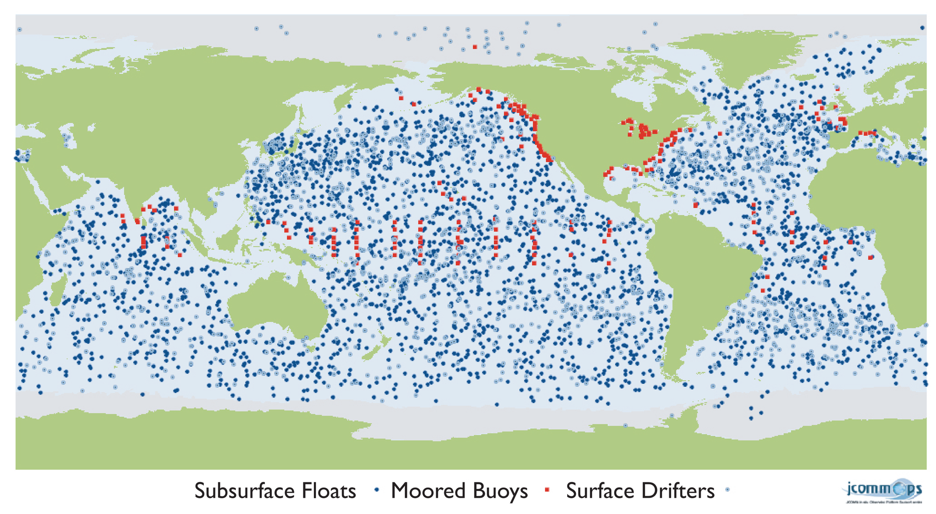

Figure 6. Positions of all hydrographic observations.

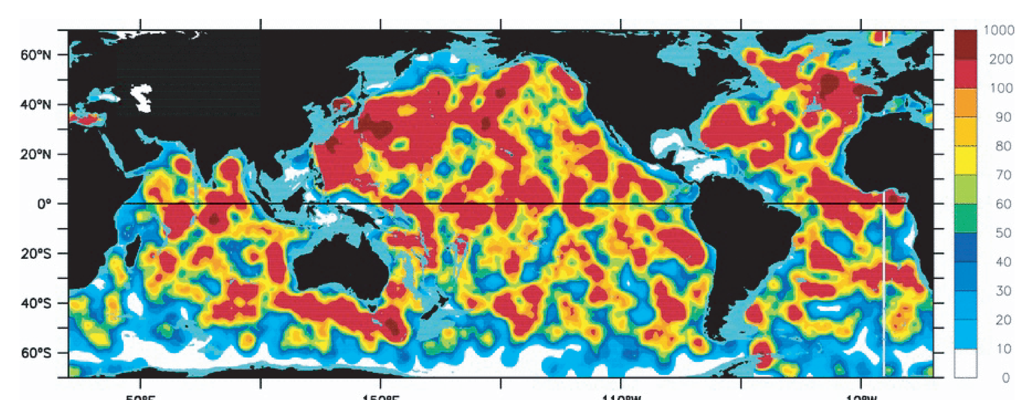

Figure 7. Density of the Argo network observations.

4. Results

The optimal interpolation (OI) scheme used by Lyman et al. [2006] and Willis et al. [2004] to produce global maps of ocean heat content in the resulting map tends to zero in the regions with no in situ data and the difference estimate reverts to the synthetic estimate. Our calculation of the standard error includes only locations with in situ observations in the global integral and is not biased by the synthetic estimates (Figure 8).

For most years in the period 1955-1968, our estimate of the standard error is significantly smaller than the estimates from the Lyman et al. OI remapping, suggesting that the sparse data coverage in this era causes the OI to overestimate the sampling error. For recent years, when Argo data are available, the OI method produces smaller error estimates than our simple sampling method.

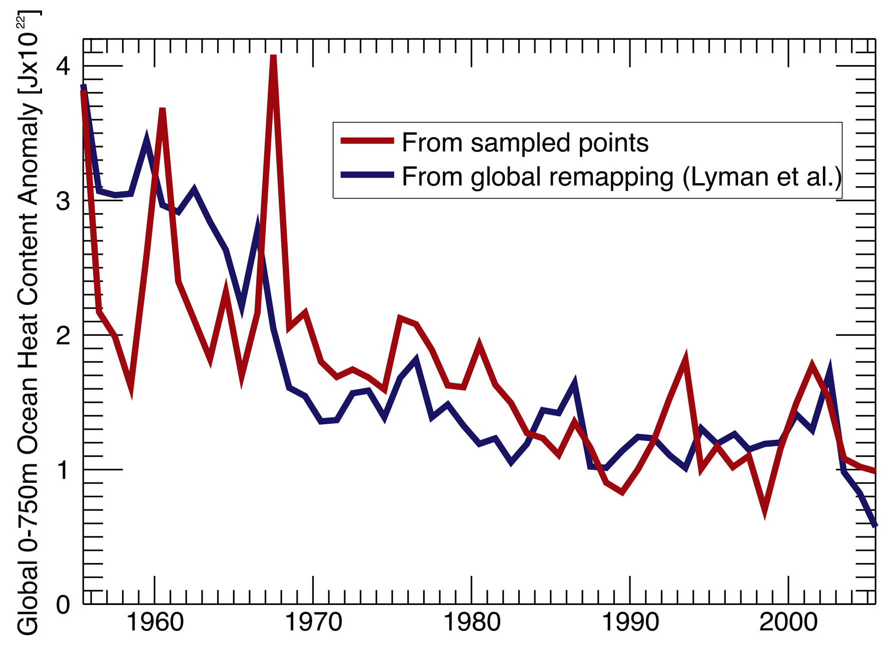

Figure 8. Standard error for globally averaged ocean heat content anomaly of the upper 750 m estimated from the AVISO SSH data set. The standard error was computed by averaging the sub-sampled data set (red line). Lyman et al. used objective analysis to remap the sampled points (black line).

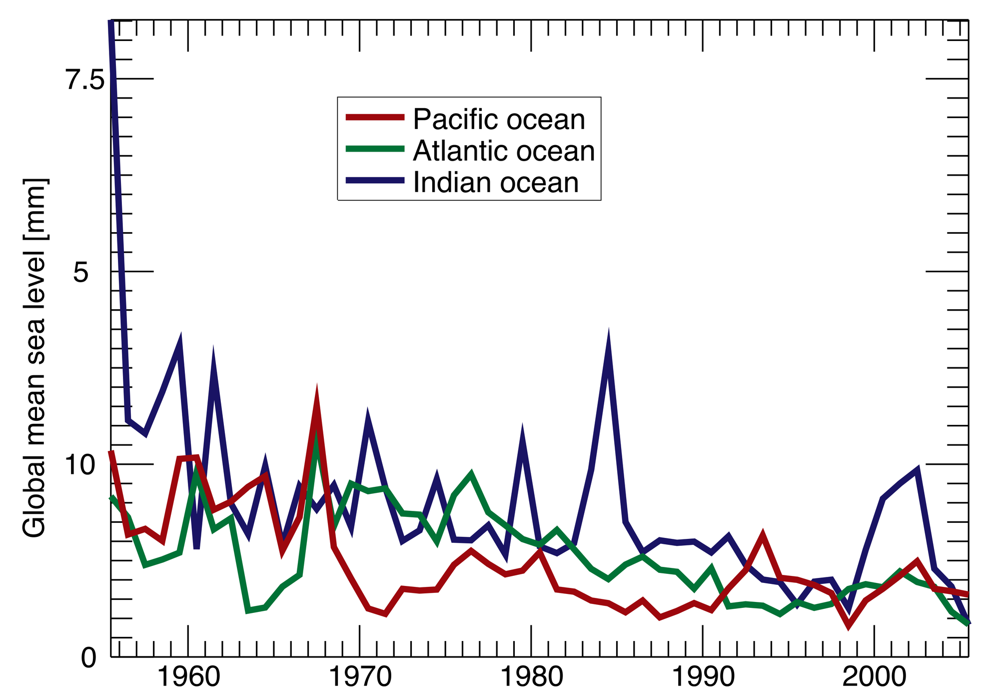

Figure 9. Standard error for global mean sea level for each of the major ocean basins from the Aviso fields calculated using the historical hydrographic sampling pattern.

In Figure 9, we estimate the standard error produced by using the historical hydrographic sampling pattern to determine annual global mean sea level (GMSL) in each of the major ocean basins. For comparison, altimetry determines GMSL to 4-5 mm every 10 days and ~1 mm annually. The increased sampling in the Southern Hemisphere is clear, but the impact of Argo since 2003 is not as clear as in the OI method of Lyman et al.

Conclusions

The optimal interpolation scheme used by Lyman et al. [2006] to remap historical ocean heat content anomalies may understate the potential for the global mean heat content to be recovered during the most sparsely sampled period (1955-1968). Other methods of historical reconstruction, like those based on variability patterns (e.g. Empirical Orthogonal Functions), could be less susceptible to the sparse sampling. However, the OI remapping appears to robustly leverage the increased number of observations from the Argo network, which would suggest that the recently observed cooling is not the result of undersampling.