Sea level change: What have we learned from satellite altimetry, satellite gravity, and ocean temperature measurements?

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Abstract

The launch of TOPEX/Poseidon (T/P) in 1992 initiated a new era in sea level change studies. The continuation of the altimeter sea level time series by Jason, the initiation of precise satellite gravity measurements with the launch of GRACE in 2002, and the densification of in situ ocean temperature measurements (Argo, etc.) have all contributed to an improved understanding of the magnitude and causes of sea level change. We review the recent results from these datasets and use them to develop a budget for present-day sea level change. The results show that these datasets provide good estimates of the total amount of sea level change, the contribution of thermal expansion, and the contribution of water from the continents (ice melt, etc.). However, a number of critical questions remain to be answered, particularly with regard to predicting the amount of sea level rise we will see in the next century.

Satellite Altimetry

These satellite altimeters measure sea level with a point-to-point accuracy of 2-3 cm along a ground track that repeats every 10 days. By averaging the sea level measurements collected in each 10-day period, estimates of global mean sea level can be computed that have been shown to have an accuracy of 4-5 mm. Figure 1 shows 10-day estimates of global mean sea level change computed from the T/P and Jason missions. Superimposed on the seasonal variations is a trend of 3.2 mm/year (after correcting for the effects of glacial isostatic adjustment (GIA) -0.3 mm/year). To ensure that this is not due to a drift in the instrument calibration, tide gauge and altimeter sea level measurements are differenced to monitor for any instrument drifts [Mitchum, 2000]. The current error estimate for the sea level trend, ±0.4 mm/year, is largely driven by errors in the tide gauge calibration [Leuliette et al., 2004]. Satellite altimetry also provides the geographic patterns of the sea level change shown in Figure 1. Figure 2 shows the rate of sea level change geographically.

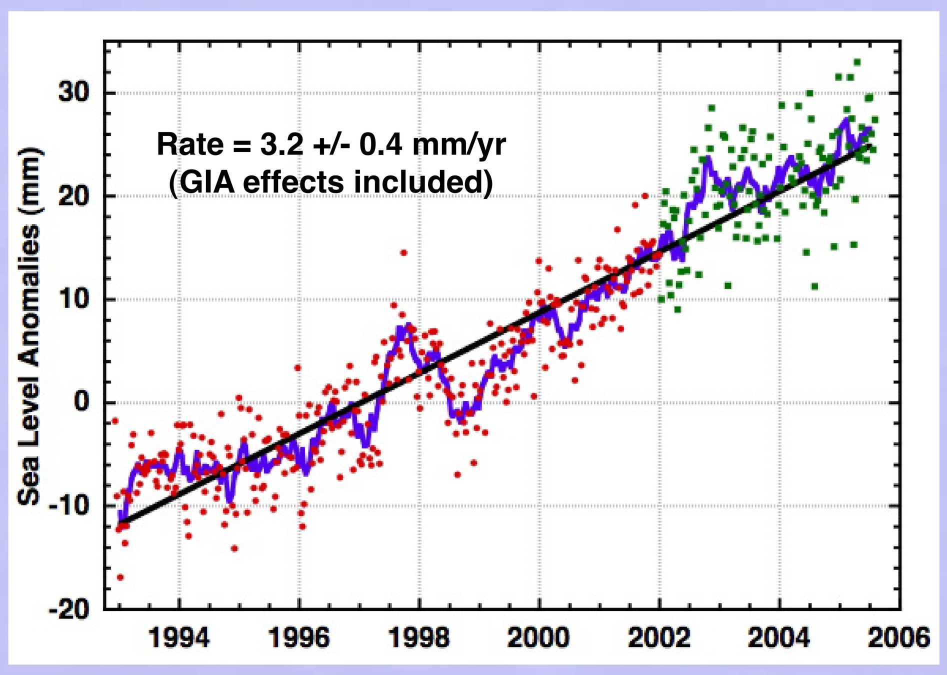

Figure 1. Global mean sea level from the T/P (red) and Jason-1 (green) missions. Seasonal terms have been removed.

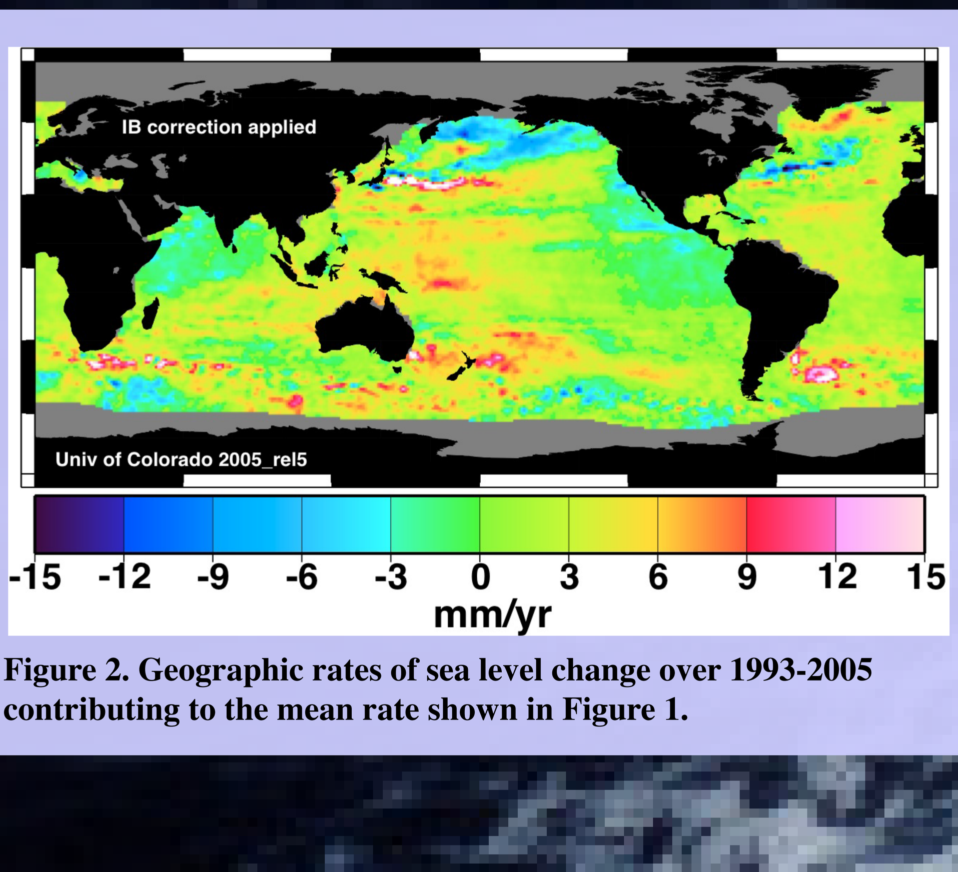

Figure 2. Geographic rates of sea level change over 1993-2005 contributing to the mean rate shown in Figure 1.

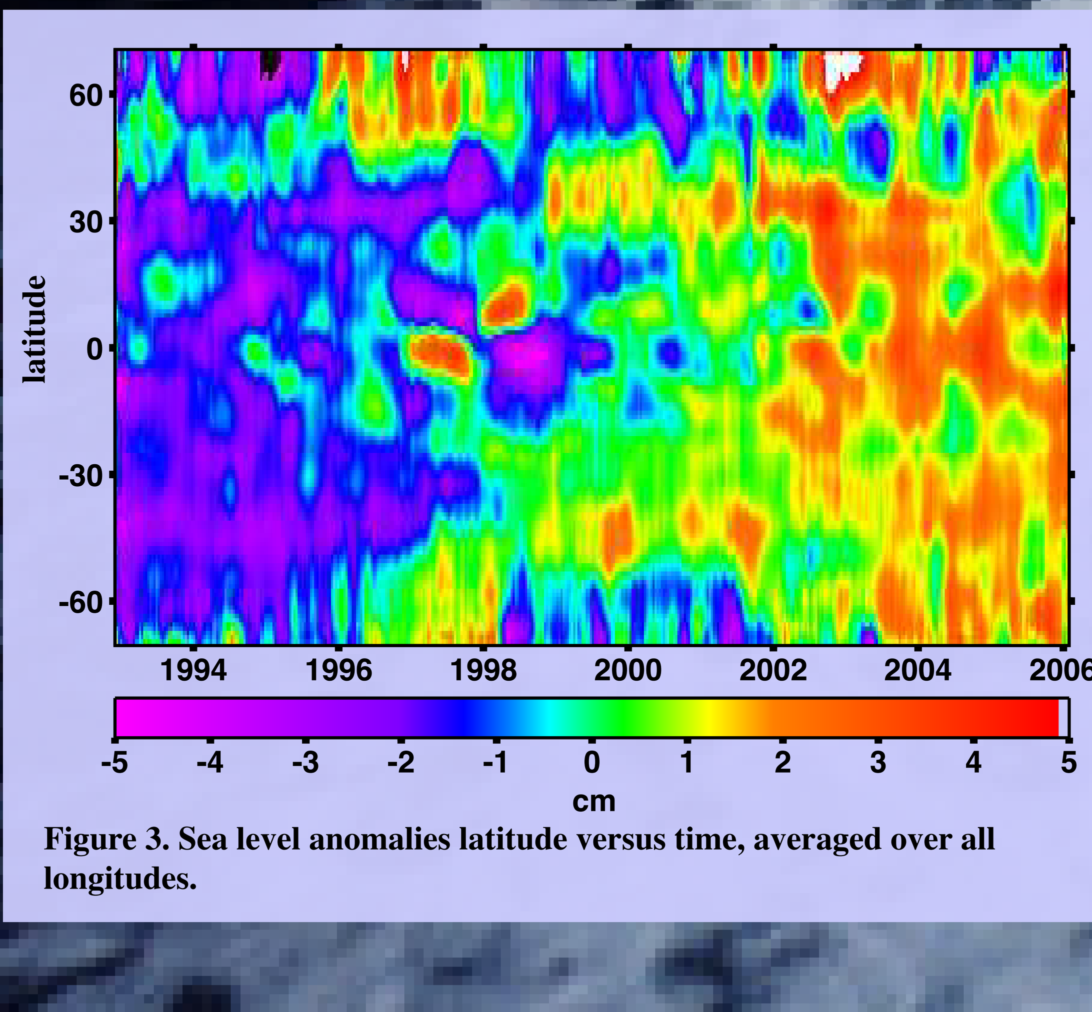

Figure 3. Sea level anomalies latitude versus time, averaged over all longitudes.

GRACE

The Gravity Recovery and Climate Experiment (GRACE) was launched in March 2002 with a primary science goal to determine variations in the Earth's gravity field at monthly intervals and at a spatial resolution of several hundred km [Tapley et al., 2004]. On secular time scales, many phenomena (post-glacial rebound, tectonic motions, etc.) contribute to temporal gravity variations, but on shorter time scales, water mass redistribution is the dominant contribution. GRACE has the unique capability of being able to directly observe the redistribution of mass from one component of the Earth system (e.g., land) to another (e.g., oceans). Although it is still difficult to extract small mass variations with the GRACE gravity field products at wavelengths less than 1000 km, one can extract information about the mass variations at long wavelengths with high accuracy.

Chambers et al. [2004] demonstrated that GRACE observes the seasonal variation of water mass in the ocean to an accuracy of better than 2 mm for each monthly measurement. The signal is caused by an exchange of water mass between the ocean and land as part of the global water cycle [e.g., *Chen* et al., 1998; *Minster* et al., 1999; *Cazenave* et al., 2000]. The accuracy of the GRACE data averaged over the entire ocean area is far higher than the accuracy when averaged over smaller regions, such as Greenland, Antarctica, or around glaciers. More important, the GRACE measurements of ocean mass provide an important constraint on observations and interpretations of melting ice sheets.

Thermosteric Sea Level

Estimating the thermosteric component of total ocean volume presents a challenge due to the relative scarcity of in situ temperature data.. Density fluctuations occur over a wide variety of spatial and temporal scales in the oceans and sampling, particularly in the Southern Hemisphere, has been historically inadequate. *Willis* et al. [2004] showed, however, that sufficient in situ measurements are available to compute globally averaged density changes related to upper-ocean (0/750 m) temperature variability with an accuracy of approximately 2 mm for 1-year averages over the period of the altimeter record. We will update the *Willis* et al. [2004] estimate of thermosteric sea level based on in situ temperature data through the present. Figure 4 shows a preliminary estimate, along with one-year averages of global mean sea level based on altimeter data [*Leuliette* et al., 2004]. Error bars in the thermosteric estimate are calculated using altimeter data as described in *Lyman* et al. [2006] and reflect the distribution of in situ data. The decrease in error over the last 3 years is due to the drastically improved coverage provided by the Argo array of profiling floats. Error bars on the total sea level have been increased to reflect the possibility of an unknown systematic drift in the altimeter data of 0.4 mm/yr [*Leuliette* et al., 2004].

Between 1993 and 2003, thermosteric sea level rose at a rate of 1.6 ± 0.3 mm/yr [*Willis* et al., 2004], accounting for approximately half of total 3.2 ± 0.4 mm/yr [*Leuliette* et al., 2004] of sea level rise during this time. The most striking feature of the thermosteric curve, however, is the rapid decrease in thermosteric sea level during the last 2 years of the time series. This is the result of net heat loss of approximately 3.2 x 10^{22} J from the upper ocean as described by *Lyman* et al. [2006]. Despite the decrease in thermosteric sea level, total sea level continued to increase. This suggests an increase in the rate of freshwater input to the ocean during these years.

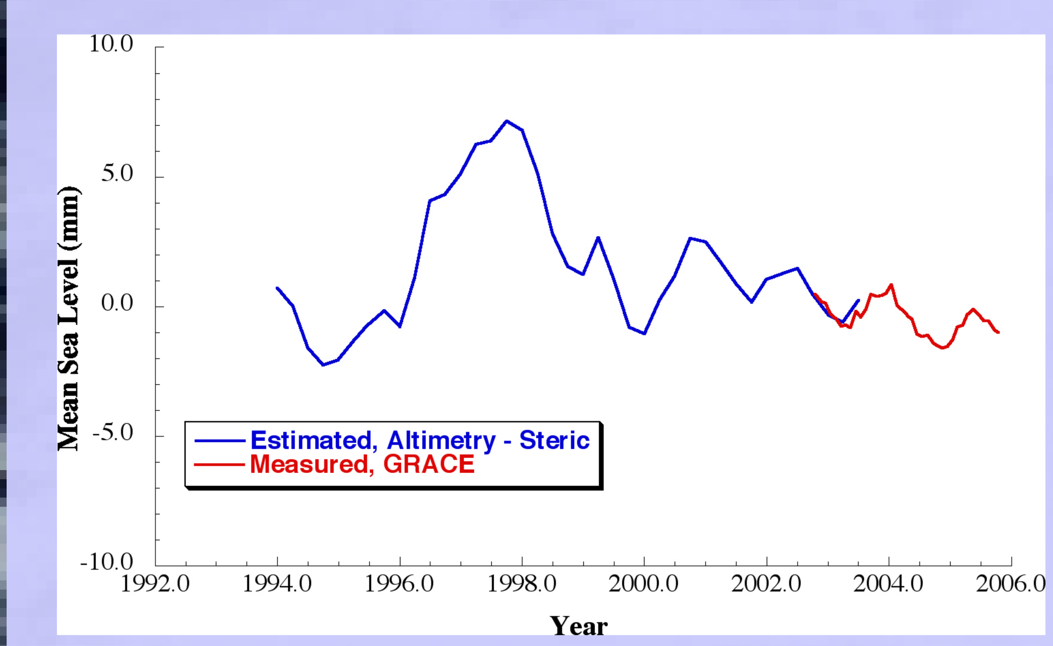

Figure 4. Interannual ocean mass measured by GRACE (red) and inferred from altimetry-steric (blue, from Willis et al., 2004). A linear trend has been removed from the altimeter-steric curve to emphasize the interannual variations. Both time-series have been smoothed with a 1-year boxcar filter. The GRACE data have been corrected for GIA using a value in the mid-point of possible values.

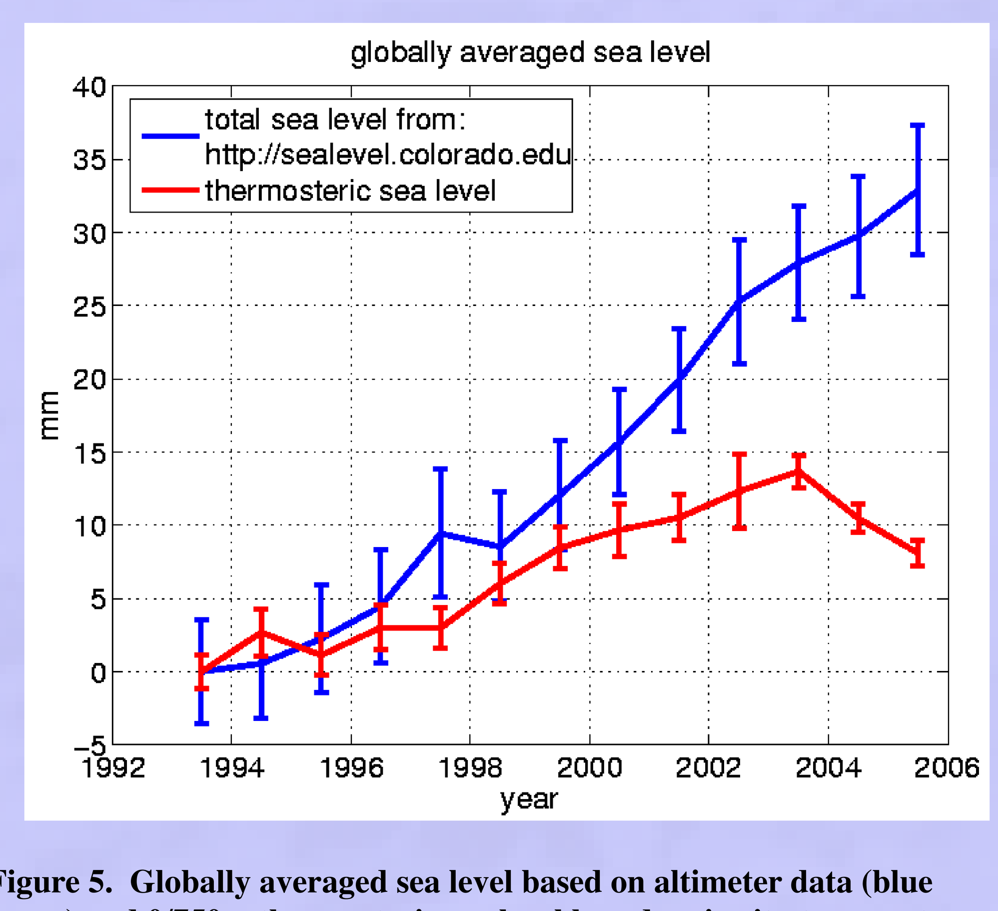

Figure 5. Globally averaged sea level based on altimeter data (blue curve) and 0/750m thermosteric sea level based on in situ temperature measurements (red curve).

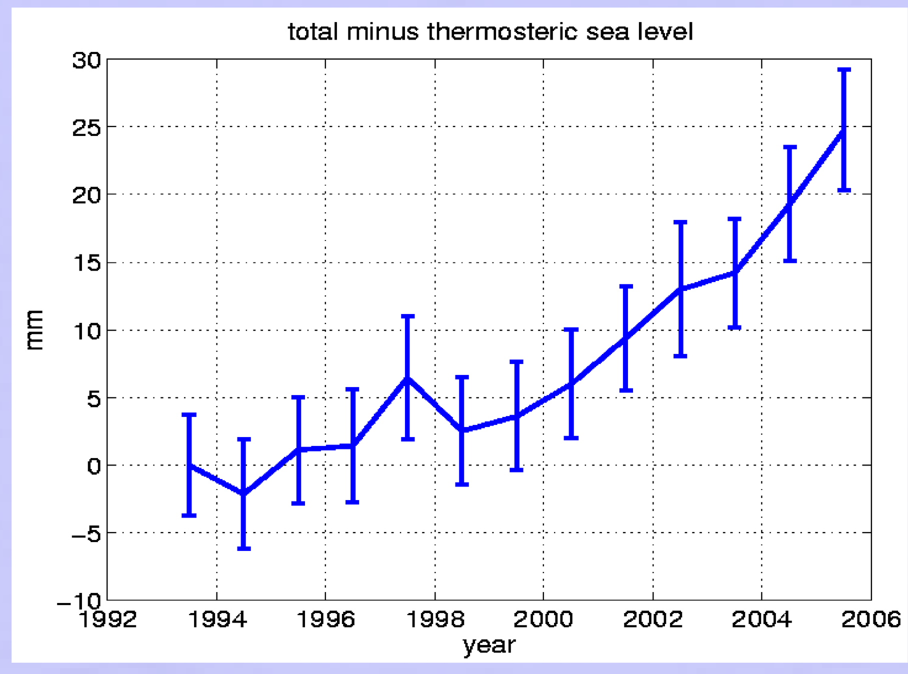

Figure 6. Inferred estimate of ocean mass variability. This is computed as the difference between total and thermosteric sea level.

Regional Changes in Sea Level

The dominant mechanism for local sea level variability depends a great deal on the temporal and spatial scales in question. We will focus primarily on large-scale variability with interannual to decadal time scales. Figure 7a shows a map of the 13-year trend in local sea level from 1993 to 2005 based on T/P and Jason satellite altimeter data [*Leuliette* et al., 2004]. Figure 7b shows the trend over the same period in 0/750 m thermosteric sea level based on in situ temperature profiles [*Willis* et al., 2004]. The two maps are similar in both amplitude and pattern suggesting that much of the regional variability in total sea level can be accounted for by changes in the temperature structure of the upper 750 m of the water column. Figure 7c shows the difference between the total and upper-ocean thermosteric trends.

The upper ocean experienced a net loss of heat between 2003 and 2005 that resulted in a decrease in globally averaged thermosteric sea level, which implies a rapid increase in the rate of mass input during this period. The regional changes in sea level for this period are shown Figure 8. The large cooling signals in the tropical N. Atlantic and S. Pacific shown in Figure 8b roughly coincide with regions of decreasing total sea level. The difference shown in Figure 8c should be viewed as preliminary and may be due in part to differences in the processing of these two data sets. If the difference in Figure 8c is reflective of mass variations, then it should show up in similar maps computed from GRACE data.

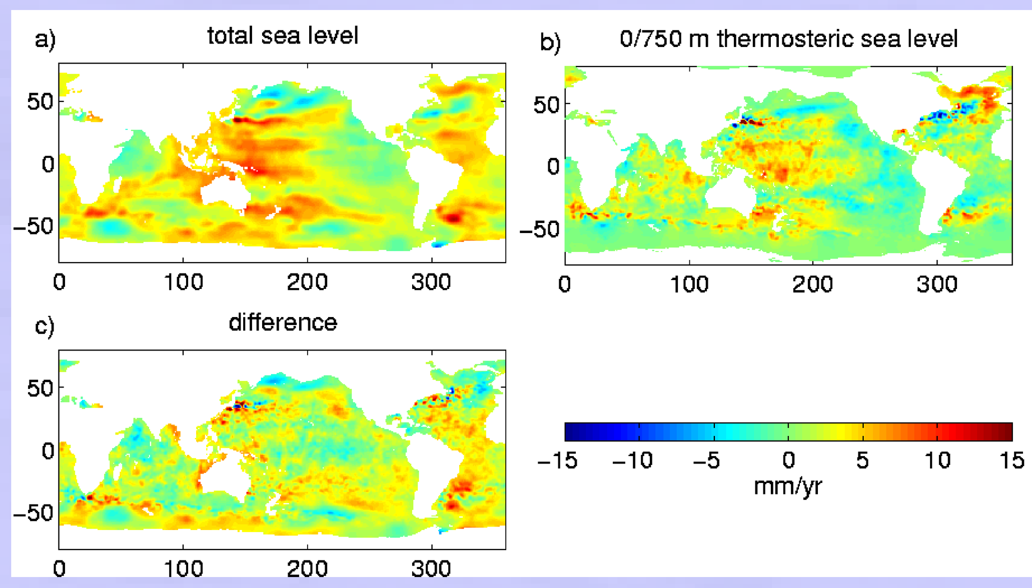

Figure 7. Trends in sea level over the period 1993 to 2005. a). Total sea level from altimeter data. b). 0/750 m thermosteric sea level from in situ data. c). The difference between a) and b).

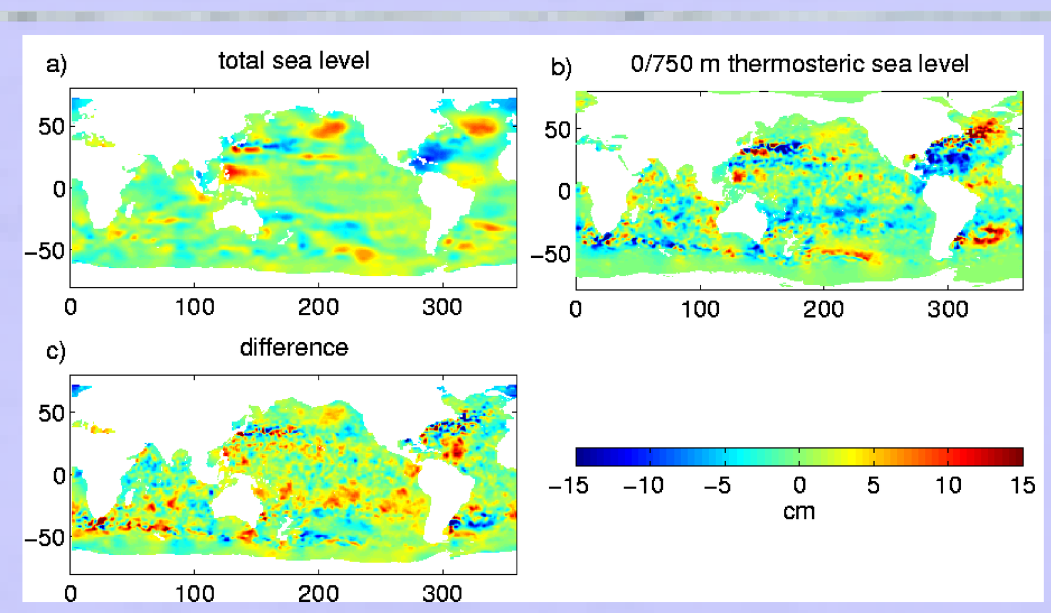

Figure 8. Change in sea level between the years 2003 and 2005. a). Total sea level from altimeter data. b). 0/750 m thermosteric sea level from in situ data. c). The difference between a) and b).

Future Work

We can compute two independent time series of change in regional and global ocean mass – one from altimeter minus thermosteric sea level differences that begins in 1992, and one from GRACE temporal gravity variations that begins in 2002. While in principle, these two estimates should agree, we do not expect realize this agreement until we better understand the processing requirements of each data set and deal with the unique errors characteristics of these methods. We will investigate not only the global mean, but also the regional patterns of ocean mass change, in hopes that the patterns might provide insight into the source of the changes in ocean mass. If an acceleration of melting in Greenland and Antarctica occurs, we expect to observe one of the patterns associated with the gravitational adjustment of the water as described by Mitrovica et al. [2001].

Observing changes in the ice sheets and discerning their contribution to sea level rise is a very difficult task as demonstrated by the widely varying results seen in the literature over the last year. Our investigation is not a substitute for direct observations of changes in the ice sheets. Nevertheless, it does provide a useful and independent assessment that will reduce the uncertainty in the contribution to sea level rise due to the melting of ice sheets and may help the cryospheric community to evaluate the relative strengths and weakness of different observational techniques.