

6-14-2008

Assessing the Globally Averaged Sea Level Budget on Seasonal to Interannual Timescales

Josh K. Willis

California Institute of Technology

D. Chambers

University of Texas, donc@usf.edu

R Steven Nerem

University of Colorado Boulder

Follow this and additional works at: https://scholarcommons.usf.edu/msc_facpub



Part of the [Marine Biology Commons](#)

Scholar Commons Citation

Willis, Josh K.; Chambers, D.; and Nerem, R Steven, "Assessing the Globally Averaged Sea Level Budget on Seasonal to Interannual Timescales" (2008). *Marine Science Faculty Publications*. 197.

https://scholarcommons.usf.edu/msc_facpub/197

This Article is brought to you for free and open access by the College of Marine Science at Scholar Commons. It has been accepted for inclusion in Marine Science Faculty Publications by an authorized administrator of Scholar Commons. For more information, please contact scholarcommons@usf.edu.

Assessing the globally averaged sea level budget on seasonal to interannual timescales

Josh K. Willis,¹ Don P. Chambers,² and R. Steven Nerem³

Received 22 August 2007; revised 24 January 2008; accepted 22 February 2008; published 14 June 2008.

[1] Analysis of ocean temperature and salinity data from profiling floats along with satellite measurements of sea surface height and the time variable gravity field are used to investigate the causes of global mean sea level rise between mid-2003 and mid-2007. The observed interannual and seasonal fluctuations in sea level can be explained as the sum of a mass component and a steric (or density related) component to within the error bounds of each observing system. During most of 2005, seasonally adjusted sea level was approximately 5 mm higher than in 2004 owing primarily to a sudden increase in ocean mass in late 2004 and early 2005, with a negligible contribution from steric variability. Despite excellent agreement of seasonal and interannual sea level variability, the 4-year trends do not agree, suggesting that systematic long-period errors remain in one or more of these observing systems.

Citation: Willis, J. K., D. P. Chambers, and R. S. Nerem (2008), Assessing the globally averaged sea level budget on seasonal to interannual timescales, *J. Geophys. Res.*, 113, C06015, doi:10.1029/2007JC004517.

1. Introduction

[2] One of the most alarming consequences of anthropogenic climate change is the effect of a warming climate on globally averaged sea level. Rising sea levels have a broad range of implications for climate science as well as considerable socioeconomic impacts for those who live in coastal and low-lying areas [*Intergovernmental Panel on Climate Change, 2007a*]. As the planet has warmed over the past century, global mean sea level (MSL) as measured by tide gauges has risen at an average rate of about 1.7 mm/a [*Church and White, 2006*], but the rate has roughly doubled over the last 15 years as recorded by satellite altimetry. Although estimates of sea level rise based on tide gauges extend back more than 100 years with reasonable accuracy, estimates of the steric and mass-related contributions to sea level rise are far more uncertain.

[3] Changes in MSL may occur owing to any one of three different physical processes. On very long timescales, changes in the volume and shape of the ocean basins can change MSL. For instance, glacial isostatic adjustment (GIA) causes a small, secular decrease in MSL of about 0.3 mm/a [*Douglas and Peltier, 2002*]. Apart from this, changes in MSL are equivalent to changes in the total

volume of seawater in the ocean. Increases in ocean volume are caused by changes in seawater density (steric component) or changes in the amount of freshwater (mass component). It is essential to quantify these components independently in order to understand and predict the Earth's response to anthropogenic climate forcing. Uncertainties in the contributions are the principal reason for the large uncertainty in projected rates of sea level rise over the next century [*Rahmstorf et al., 2007; Intergovernmental Panel on Climate Change, 2007b*].

[4] Since mid-2003, the Argo array of profiling floats and the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission have made independent observations of the steric and mass components of sea level rise for the first time. Using these data, we investigate recent variability in the components of MSL on seasonal to interannual timescales and their agreement with the independent observation of total sea level rise from satellite altimetry.

[5] A recent comparison of altimeter, GRACE and in situ data was carried out by *Lombard et al. [2007]*. Since that work, however, the rapid decrease in steric sea level beginning in 2003 was found to be the result of instrument biases in data from both expendable bathythermographs (XBTs) as well as a small number of specific Argo floats [*Willis et al., 2007*] (see also J. K. Willis et al., In situ data biases and recent ocean heat content variability, submitted to *Journal of Atmospheric and Oceanic Technology*, 2007) (hereinafter Willis et al., submitted manuscript, 2007). In the present analysis, these biases have been eliminated by using only profile data from Argo floats that were unaffected by the problems described by Willis et al. (submitted manuscript, 2007). No XBT data were used.

¹NASA/Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

²Center for Space Research, University of Texas at Austin, Austin, Texas, USA.

³Colorado Center for Astrodynamic Research, Department of Aerospace Engineering Sciences, Cooperative Institute for Research in Environmental Science, University of Colorado at Boulder, Boulder, Colorado, USA.

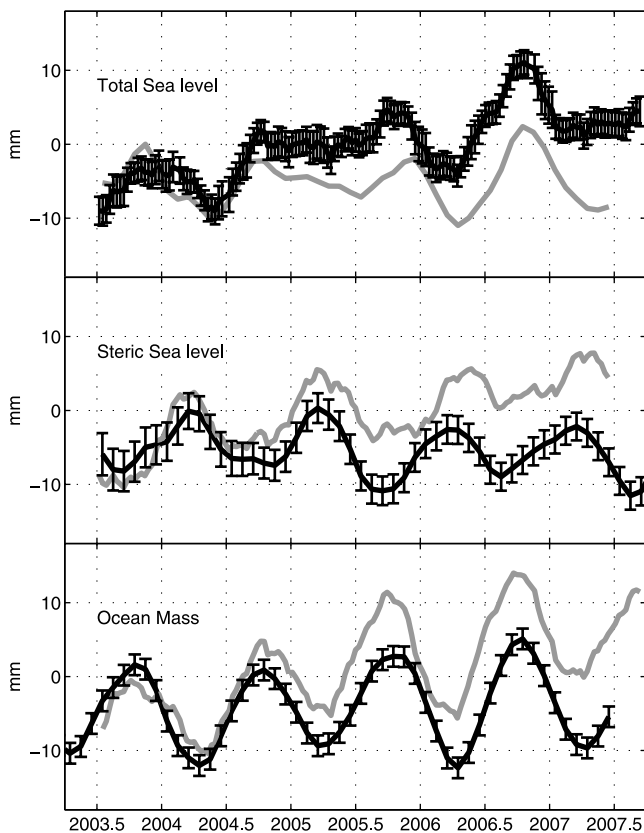


Figure 1. Global mean sea level variability and its components. (top) Total sea level, (middle) the steric component of sea level, and (bottom) ocean mass variability. Black lines show the observed estimates from (top) the satellite altimeter, (middle) Argo floats, and (bottom) GRACE, respectively. Gray lines show the inferred estimates, computed by adding or subtracting the other two observational estimates as in equation (1). Error bars are 1 standard error and represent random errors only on the observed estimates.

Additional refinements to the GRACE and Jason data have also been made, as described below.

2. Altimeter Data

[6] Sea surface height anomaly data from the Jason-1 satellite altimeter were used to provide estimates of MSL variability [Leuliette *et al.*, 2004]. All of the standard corrections to the altimeter data were applied including removal of ocean tides and an inverted barometer correction. In May of 2007, an updated version of the Jason-1 Geophysical Data Record (GDR B) was released for all of the cycles from January of 2002 through July of 2007. This release provided a continuous record with consistent processing and reconciled differences in global MSL bias and drifts that occurred in earlier versions of the GDR. Finally, a 0.3 mm/a trend was added to account for GIA [Douglas and Peltier, 2002].

[7] Figure 1 shows the time series of MSL from Jason-1 smoothed with a 60-d running mean filter (black line, top panel). The filter was necessary in order to reduce the

effects of a well-known periodic error in TOPEX/Poseidon and Jason-1 data related to the satellite nodal period. Figure 2 shows the total sea level curve with the seasonal cycle removed.

[8] Jason-1 data are restricted to ice-free regions between $\pm 66^\circ$, covering over 90% of ocean area. Nevertheless, barotropic transports of ocean mass into and out of this domain do account for small fluctuations in the MSL time series. Although its magnitude is comparable to the measurement accuracy of the altimeter time series, this signal is observed by GRACE (see Figure 3) and the estimate of ocean mass is adjusted to account for it as described in the following section. With this caveat, the MSL time series provides a first-order estimate of changes in the ocean's total volume. It should equal the sum of the ocean mass time series from GRACE and the steric sea level time series from Argo (gray line, Figures 1 and 2, top).

[9] The error bars for this curve represent one standard error and were computed by combining the random error in a 60-d average with the overall accuracy of MSL for a single 10-d average with the accuracy of MSL for a single 10-d cycle of the altimeter (~ 5 mm), determined by comparison with tide gauges [Leuliette *et al.*, 2004]. This gives a standard error of approximately 2 mm for an individual 60-d average. As with all of the error estimates presented here, these errors reflect only random errors that have been quantified in some way, and unknown systematic errors may remain.

[10] The amplitude and phase of the seasonal cycle of MSL were computed by least squares fit of an annual

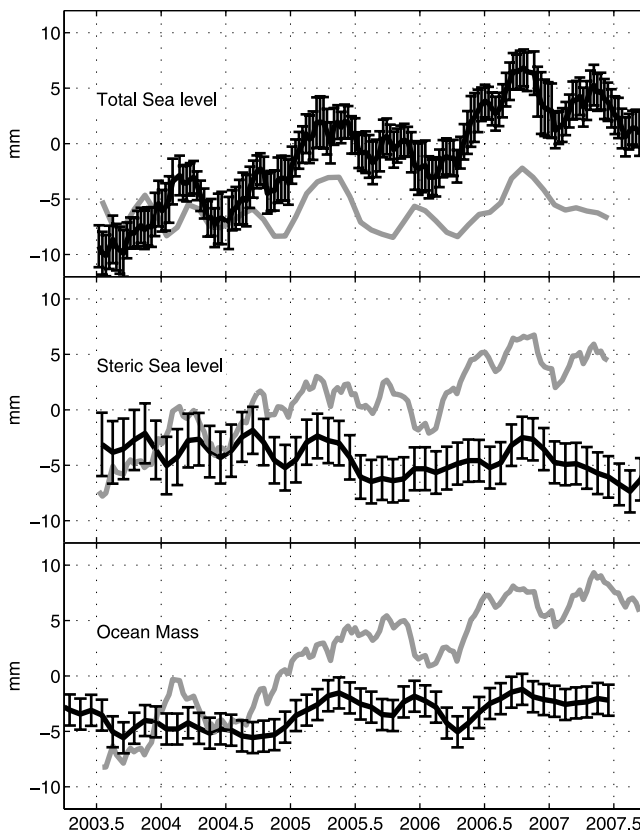


Figure 2. Same as Figure 1, but with the seasonal cycle removed.

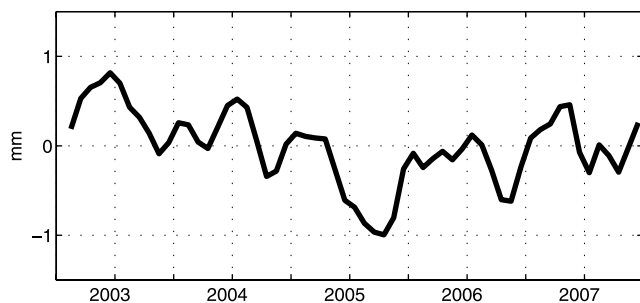


Figure 3. Difference between ocean mass variations from GRACE averaged globally and averaged between $\pm 66^\circ$ latitude.

harmonic and trend from July of 2003 through June of 2007, which is the period common to all of the estimates. As summarized in Table 1, the amplitude and phase of the seasonal cycle are 3.2 ± 1.3 mm and $250^\circ \pm 23^\circ$, and the trend is 3.6 ± 0.8 mm/a. Here the error bounds represent the 95% confidence interval from the least squares fit.

3. GRACE

[11] Satellite measurements of the Earth's time varying gravity field are provided by GRACE. These are used to infer movement of water mass over the Earth's surface [Wahr *et al.*, 1998]. In the present analysis, we use the most recent gravity field solutions (Release-04) from the Center for Space Research (CSR) at the University of Texas, Austin, from July of 2003 through June of 2007 [Bettadpur, 2007]. We compute ocean mass variations as described by Chambers *et al.* [2004], including replacing the degree 2, order 0 coefficients with those from a satellite laser ranging analysis [Cheng and Tapley, 2004] and adding an estimate of geocenter motion to account for the degree 1 components of the gravity field, which GRACE does not observe. In this analysis, we use new, monthly geocenter estimates calculated by Swenson *et al.* [2008], based on an ocean model and GRACE data over the land.

[12] A correction for glacial isostatic adjustment (GIA) has also been applied to account for displacements of the Earth's crust following the end of the last ice age. To GRACE, this motion appears as a secular trend in the gravity field. It is not, however, due to the instantaneous redistribution of water over the Earth's surface and must therefore be removed. The GIA model is from Paulson *et al.* [2007], based on the ICE-5G glaciation model and a solid Earth model tuned in part to match GRACE signals over Hudson's Bay and Fennoscandia, where the GIA signal is the largest. We note that the GIA correction has a significant effect on the ocean mass trend from GRACE. When interpreted as water mass equivalent at the surface of the Earth, the correction increases the GRACE trend by nearly 1 mm/a. Uncertainty in the GIA correction is estimated to be at most $\pm 20\%$ (J. Wahr, personal communication, 2007).

[13] The GRACE project models atmospheric mass and some ocean barotropic variations, and observations of the gravity field are processed as departures from these models. For oceanographic analyses, it is necessary to add back the modeled ocean and atmospheric mass variations to the

distributed GRACE data [Chambers, 2006a]. Furthermore, this step is necessary for comparison with the Jason-1 data, which includes part of the signals that were modeled. In the global average, however, the signal measured by GRACE then reflects mean ocean bottom pressure, which includes the mass of the atmosphere that overlies the ocean. This is not equivalent to the MSL change since the ocean is essentially incompressible. For comparison with the altimeter data, the mean ocean bottom pressure was converted to MSL by simply removing the time-variable mass of the atmosphere averaged over the global ocean. This can be calculated easily from the atmosphere/ocean model distributed with the monthly GRACE data, since the ocean model has no such time-variable, mean mass component [Flechtner, 2007].

[14] We have used a new averaging function that was designed to reduce leakage from land hydrology (including ice sheets) to a level of less than 0.1 mm RMS [Chambers *et al.*, 2007]. To be consistent with the Jason-1 data, we have restricted the averaging function for the GRACE gravity coefficients to latitudes less than 66° .

[15] The difference between the global mean and $\pm 66^\circ$ mean of ocean mass observed by GRACE is small but significant (< 1 mm standard deviation) and has intra- and inter-annual fluctuations (Figure 3). This suggests a small but significant exchange of mass between the Arctic and rest of the global ocean that is consistent with a recent study by Morison *et al.* [2007], who observed large ocean bottom pressure fluctuations in the Arctic Ocean.

[16] The time series of ocean mass from GRACE between $\pm 66^\circ$ is shown in Figure 1 (bottom). For consistency with the altimeter data, a 60-d running mean smoother has been applied. Error bounds for this curve are estimated to be about 2 mm for a single month based on of the GRACE covariance, leakage from hydrology, and missing ocean areas based on models. These error bounds are reduced to 1.4 mm by the 60-d mean.

[17] This time series represents changes in MSL related to the exchange of freshwater between the land and the oceans, with a small correction to account for ocean mass exchange with high-latitude ocean regions. It should equal the difference between the time series of total and steric sea level. A strong seasonal cycle with amplitude of 6.8 ± 0.6 mm and phase of $261^\circ \pm 5^\circ$ is the dominant feature. This is primarily caused by the seasonal transfer of water to land through evaporation and precipitation and the return of water to the ocean through continental runoff. Again, Figure 2 shows the seasonally adjusted ocean mass curve. A positive

Table 1. Seasonal Cycle Amplitudes, Phase, and Slope of Trend for Components of Sea Level Rise and Total Sea Level as Measured by Altimeter^a

	Amplitude	Phase	Slope
Steric	3.7 ± 0.8 mm	$104^\circ \pm 13^\circ$	-0.5 ± 0.5 mm/a
Mass	6.8 ± 0.6 mm	$261^\circ \pm 5^\circ$	0.8 ± 0.8 mm/a
Sum of components	3.7 ± 1.0 mm	$239^\circ \pm 16^\circ$	0.3 ± 0.6 mm/a
Altimeter	3.2 ± 1.3 mm	$250^\circ \pm 23^\circ$	3.6 ± 0.8 mm/a

^aThese were determined by least squares fit of a sine, cosine, slope, and constant to each 3-year time series shown in Figure 1, over their common period from July of 2003 through June of 2007.

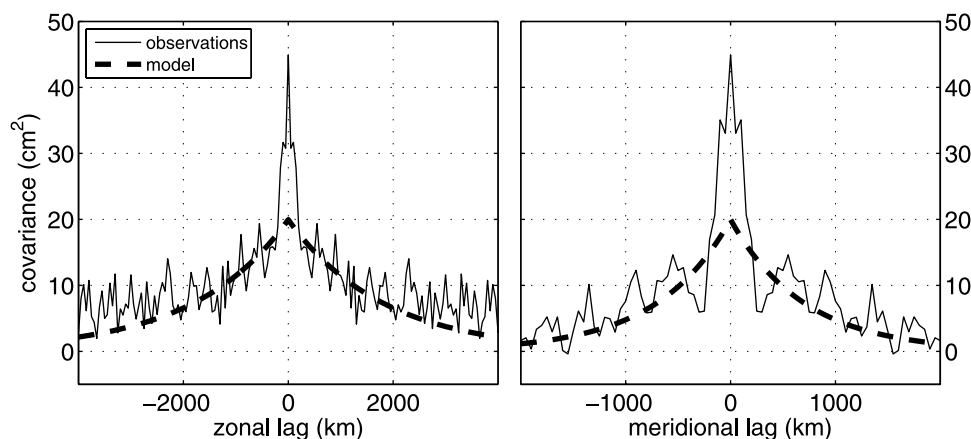


Figure 4. (left) Zonal and (right) meridional covariance functions computed from the data (thin lines) and modeled (thick, dashed lines).

trend of 0.8 ± 0.8 mm/a is also present in the ocean mass estimate, although it is substantially smaller than the trend in the altimeter data.

[18] The uncertainty on the trend estimate includes the formal uncertainty (± 0.4 mm/a), the uncertainty in the GIA correction (± 0.2 mm/a), and an uncertainty related to a long-period alias of the K2 tide (± 0.2 mm/a). The K2 tide aliases to a 1400-d (~ 3.8 -year) period in the GRACE orbit. Any error in the K2 tide will alias into a similar periodic signal in the GRACE data. Estimating a trend over a period smaller than this alias period can bias the result. There is some evidence that a small K2 error exists in the GRACE data. The Center for Space Research (CSR) and GeoForschungs-Zentrum (GFZ) processing centers use similar tide models, except for the K2 constituent (F. Flechtner personal communication, 2007), and there is a distinct 3.8-year period in the difference between ocean mass time series computed separately with the CSR and GFZ data, based on nearly 5 years of data. We estimate the uncertainty due to this possible K2 alias as the difference between trends estimated with and without a 3.8-year sinusoid, which for the CSR data is 0.18 mm/a. The difference for trends in the GFZ data estimated with and without a 3.8-year sinusoid is 0.57 mm/a, suggesting that the GFZ data may have a larger K2 error. This is the primary reason we use CSR processed GRACE data in this study. If a 3.8-year sinusoid is estimated and removed from the data, the GFZ and CSR time series are nearly identical.

4. Argo Data

[19] In situ temperature and salinity profiles from the Argo array of profiling floats were used to estimate changes in ocean density. All profiles from instruments with erroneous pressure values as described by Willis et al. (submitted manuscript, 2007) were discarded prior to analysis. Delayed-mode data were used where available, and Argo quality control flags were used to eliminate spurious measurements. Data from marginal and inland seas were also excluded. Additional quality control was performed in two steps. First, all profile data were grouped together in 10° latitude bands and visually inspected to remove gross outliers. For each profile, steric height at the

surface was then computed relative to 900 m. Steric height at the location of each profile was also computed from the WOCE gridded hydrographic climatology (WGHC) [Gouretski and Koltermann, 2004]. WGHC steric height was then subtracted from the observed steric height and data were divided into $5^\circ \times 5^\circ$ horizontal boxes. A standard deviation check was performed in each box, and steric heights more than three standard deviations away from the $5^\circ \times 5^\circ$ mean were removed. Less than 1% of Argo data were eliminated using this procedure. After quality control, about 193,000 profiles from 3197 floats remained between July of 2003 and the June of 2007.

[20] The 900 m depth was chosen to provide maximal spatial and temporal coverage, as many floats do not profile deeper than 1000 m, particularly at low latitudes. While steric changes below 900 m do contribute to sea level rise in specific regions and on long timescales, previous work suggests that seasonal to interannual variations are largely confined to the upper few hundred meters in the global average [Antonov et al., 2005; Chambers et al., 2004].

[21] Removing the time mean prior to mapping helps to reduce aliasing of longer-term variability into the monthly maps. For this reason, monthly objective maps of steric sea level variability were made in two steps. First, an objective map [Bretherton et al., 1976] of the time mean over the period from mid-2004 through mid-2006 was computed using steric height relative to the WGHC as a first guess. To make the time-mean map computationally feasible, data were first averaged in 2° longitude by 1° latitude bins, which were recentered to their geographic means and used as input data for the objective map. Monthly objective maps of the Argo data were then made relative to the time mean.

[22] As in work by Willis et al. [2004], the covariance of the data was found to be consistent with a two-scale covariance function (Figure 4). However, in the present analysis the narrow Gaussian component of the covariance function was modeled as part of the noise so that only basin and gyre-scale variability would be mapped. In addition, the assumption of isotropy in the covariance function was relaxed. The resulting covariance function, used for all objective maps, was an exponential function with an 1800 km e-folding scale in the zonal direction and a 700 km e-folding scale in the meridional direction. As

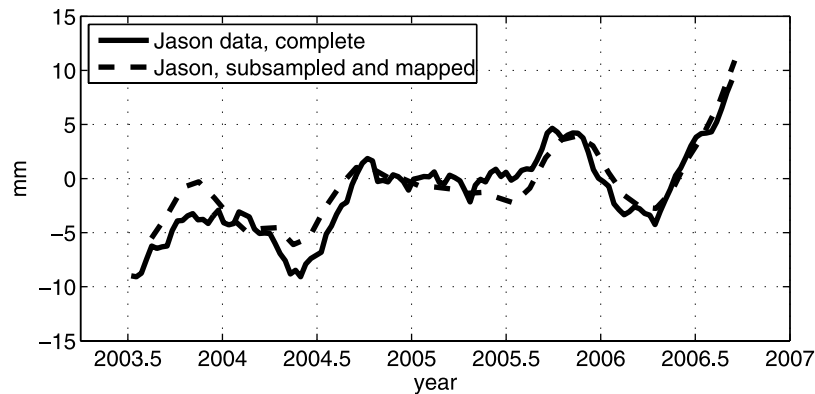


Figure 5. Global mean sea level from Jason estimated by subsampling and mapping the Jason data (thin line) and made using all Jason data (thick line). The latter is the same as the curve from the top plot of Figure 1. Discrepancies between these curves are caused by undersampling in the Argo array or errors in the mapping procedure.

illustrated by Figure 4, this is in good agreement with observed zonal and meridional covariance functions of steric height computed from the Argo data. A relatively large noise-to-signal ratio of 1.9 for the climatology and 1.3 for the monthly maps was necessary in order to account for the energetic mesoscale eddy field, visible as a tall, narrow peak in the observed covariance function.

[23] Monthly maps of steric height were then globally averaged to produce the time series of steric MSL for the period from July of 2003 through June of 2007. For consistency with the total and mass components of sea level, a 60-d running mean filter was applied. The resulting estimate of steric sea level variability is shown in the middle plot of Figure 1. The errors bars were determined as part of the objective mapping procedure [Bretherton *et al.*, 1976] and were found to vary from 4.0 to 2.6 mm for a single month, decreasing with time as Argo coverage improved. The 60-d running mean smoother reduced the errors to 2.8 to 1.8 mm as shown in Figures 1, 2, and 6.

[24] As an additional check on the accuracy of the steric MSL time series, a sampling experiment was carried out using Jason data as a proxy for the Argo profile data. Jason data were first interpolated to the time and location of each Argo profile. Monthly maps of sea level were then estimated from the subsampled Jason data using the same mapping technique that was applied to the Argo data. The resulting estimate of MSL compares very well with the estimate made using all of the Jason data (Figure 5). The RMS difference between the two is 1.5 mm, which is smaller than the estimated random error in the steric MSL estimate discussed above. The trend in the MSL time series was reduced by about 0.4 mm/year by subsampling the data to match Argo data distributions. However, this is much smaller than the remaining discrepancy in the sea level budget trends as discussed below. This suggests that the Argo data density and mapping procedures are adequate to resolve the MSL time series over this period.

[25] Figures 1 and 2 show the time series of upper ocean steric sea level with and without the seasonal cycle, respectively. To the extent that steric variations are confined to the upper ocean on seasonal to interannual timescales, this curve should be equal to the difference between the time

series of total sea level and the mass component of sea level. The seasonal cycle of steric sea level has an amplitude and phase of 3.7 ± 0.8 mm, and $104^\circ \pm 13^\circ$, respectively. This is almost 180° out of phase with the total and mass components of sea level, consistent with the results of Chambers *et al.* [2004], Chambers [2006a], Chen *et al.* [2005], and Lombard *et al.* [2007]. The trend in steric sea level is -0.5 ± 0.5 mm/a over the study period. This is in good agreement with the corrected heat content estimate made using Argo data from Willis *et al.* (submitted manuscript, 2007), and does not reflect the spurious cooling reported by Lyman *et al.* [2006].

[26] Although not shown, halosteric and thermosteric components of steric sea level were also computed. The trends in the thermosteric and halosteric components were -0.9 mm/year and 0.3 mm/a, respectively. However, the RMS variability of the globally averaged halosteric time series was only 0.9 mm. It accounted for only 11% of the variance of the steric sea level curve and its month to month fluctuations were not significant relative to the error bounds.

5. Sea Level Budget

[27] The equation for the MSL budget may be expressed as

$$h_{\text{TOT}} = h_{\text{STERIC}} + h_{\text{MASS}}, \quad (1)$$

where h_{TOT} is total sea level (observed by Jason-1), h_{STERIC} is the steric component of sea level (observed by Argo), and h_{MASS} is the component due to changes in ocean mass (observed by GRACE). The sea level budget is closed observationally, if the right and left sides of this equation agree within the error estimates of each term.

[28] The observational estimates of each term in equation (1) are shown as black lines in Figures 1 and 2. The gray lines show inferred estimates of each term, computed by adding or subtracting the other two. Although there is reasonable agreement between the inferred estimates and the observational estimates in the first year of each time series, the inferred and observational estimates rapidly diverge after mid-2004. By the beginning of 2005,

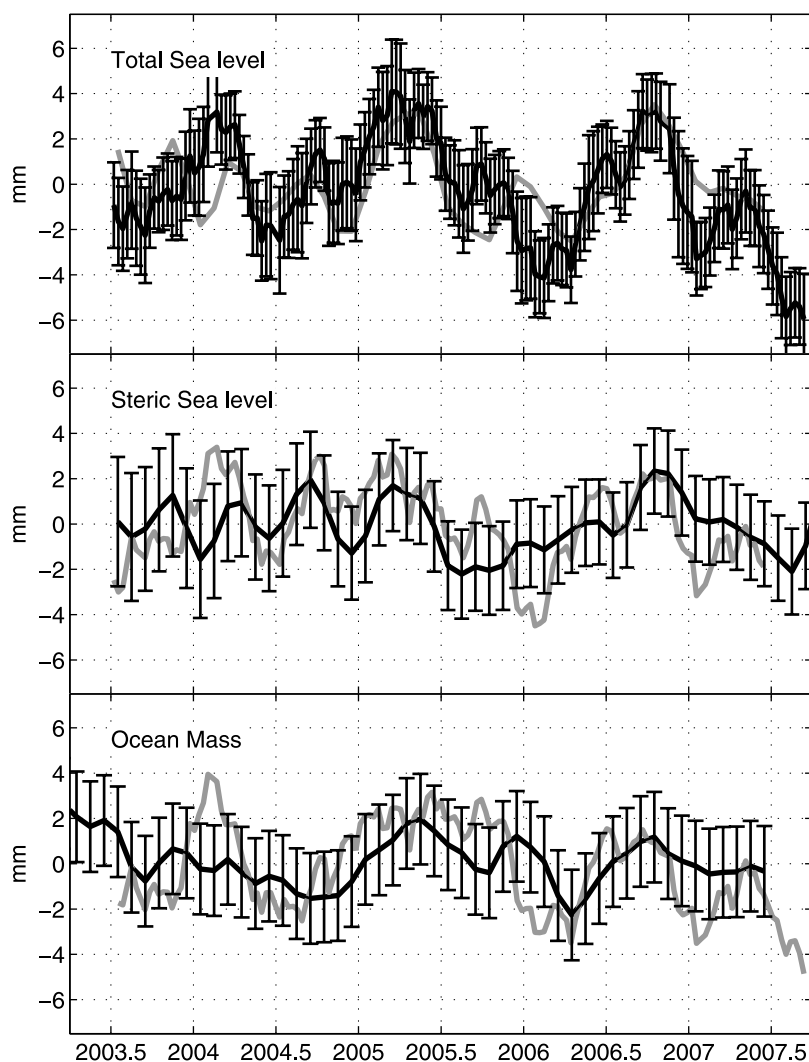


Figure 6. Same as Figure 2, but with the trend removed as well.

all three of the inferred estimates of MSL lie well outside the random error bars of the observational estimates. Note, however, that the seasonal and interannual fluctuations of the inferred estimates are very similar to those of the observational estimates. Some features agree well, such as the rapid increase in early 2005 and the slight decrease after mid-2005 and early 2007 of seasonally adjusted MSL and ocean mass. The primary difference between the inferred and observational estimates appears to have a long timescale relative to the 4-year record.

[29] The sea level budgets of the seasonal cycle and trend are summarized in Table 1. The seasonal cycle of the sum of the components is in good agreement with that of the altimeter. Both the phase and the amplitude of the seasonal cycle agree to within the expected observational error bounds. The discrepancy between inferred and observational estimates is most readily visible in the trend. The trend in the sum of the components is 0.3 mm/a , about 3.3 mm/a smaller than that of the altimeter. This is well outside of the expected 0.8 mm/a random error bounds for the altimeter-based observations of the 4-year rate of sea level rise.

[30] The cause of the divergence between the measurements of total sea level and its components is not yet

known, however, the disagreement is much larger than estimates of random error. This is illustrated most clearly by the fact the gray lines fall outside the range of the error bars in all six plots of Figures 1 and 2 after the beginning of 2004.

[31] This suggests that an unexplained systematic error remains in at least one of the three observing systems. Furthermore, the error appears to be fairly linear over the period of the present analysis. This can be illustrated by removing the trends as well as the seasonal cycles from all three records (Figure 6). With the trends removed, the inferred and observational estimates are in excellent agreement. The RMS difference between the observational and inferred estimates of total MSL (Figure 6, top) is 1.6 mm . This is significantly smaller than the combined random error of the three time series ($\sim 3 \text{ mm}$), suggesting that the random error estimates may be somewhat conservative. This further supports the idea that the remaining systematic error has a timescale significantly larger than the 4-year period considered here.

[32] Figure 7 shows the spatial distribution of the trend in total sea level from Jason, total sea level minus the mass component from GRACE, and steric sea level from Argo,

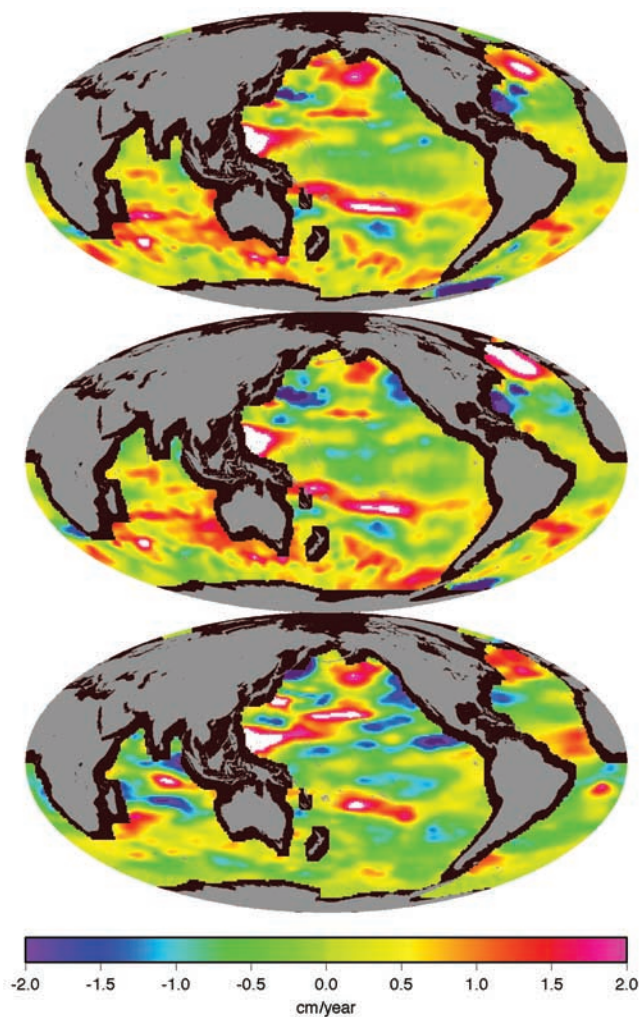


Figure 7. Spatial distribution of (top) the trend from July of 2003 through the June of 2007 in total sea level from Jason, (middle) the difference between Jason and GRACE, and (bottom) steric sea level from Argo. Units are in cm/a.

respectively. A large positive trend is visible in the Jason data that stretches from the central Indian Ocean eastward to the southern tip of Chile. The GRACE data contains no significant trend in this region, which is illustrated by the fact that the signal is virtually unchanged when the ocean mass signal is subtracted. This is not surprising as a large interbasin mass exchange due to surface forcing is unlikely on these intradecadal timescales. The Argo data, however, does not show a significant positive trend in steric sea level in this region as would be expected if the trend in the altimeter were the result of upper-ocean warming. A similar discrepancy appears in the South Atlantic Ocean. This Southern Hemisphere signal appears to be the primary cause of the discrepancy in the global sea level budget.

[33] A significant discrepancy is also seen in the trend maps of the far North Atlantic, near Greenland. The extent of this region is small and removing it changes the trend in the global average by only 0.1 mm/a. The trend in GRACE there, however, appears to be significantly larger than the trend in either Jason or Argo. A number of nonoceanographic

signals appear in the GRACE data in this region. These include postglacial rebound and large terrestrial signals from Greenland, which may “leak” into the ocean as described in section 3. The large GRACE trend in this region may also be caused by a correlated error in GRACE data that is not fully removed in the averaging or “destriping” methods [e.g., Swenson and Wahr, 2006 or Chambers, 2006b]. Further investigation will be necessary to determine the cause of this large mass signal in the North Atlantic.

6. Discussion and Conclusions

[34] Further investigation will be necessary in order to identify and correct the remaining systematic error, as a number of possibilities exist. These include changes in the processing of altimeter data (release of updated GDR, changes in sea state bias, etc.), undetected biases in the Argo data such as the pressure bias recently discovered in a small set of floats [Willis *et al.*, 2007, also submitted manuscript, 2007], or errors or changes in the GRACE background models. For instance, we have already noted that several possible systematic errors may exist in the GRACE observation related to the GIA correction, a long-period alias of the K2 tide, and the geocenter correction. However, even if all of these errors added systematically to cause an underestimate of ocean mass increase in GRACE, the error would not be larger than 1 mm/a based on conservative estimates. This is still not enough to close the budget in the trend, although it would bring it slightly closer. We also note that these effects are very long wavelength and would not be expected to appear as the smaller wavelength signals in the trend maps that are observed (Figure 7).

[35] Examination of the spatial distribution of sea level trends over this period suggests that much of the remaining discrepancy lies in the Southern Hemisphere. Rapid increases of several cm in this region appear in the Jason data, but are not reflected in either steric height from Argo or ocean mass from GRACE. The pattern of this discrepancy is somewhat similar to patterns of surface wave height corrections made to the altimeter data. However, a more careful examination of these discrepancies will be required before the sea level budget can be closed over the 4-year record.

[36] Apart from the trend, agreement between the three different observing systems is encouraging. This suggests that the global ocean observing system is adequate for closing the sea level budget on seasonal to interannual timescales based on the random error estimates presented here. On longer timescales, however, deep steric changes will undoubtedly become important. Once the source of the differences in the trend is understood and a longer time series becomes available, these three components of the global ocean observing system will also provide information about steric variations in the deep ocean that are currently not observed.

[37] As expected, the seasonal cycles of the components of MSL variability are almost 180° out of phase. This reflects the uneven distribution of the continents between the northern and southern hemispheres and the difference in timing between ocean heating/cooling and river runoff. Steric sea level has a seasonal amplitude of 3.7 ± 0.8 mm, peaking in early April. Since two thirds of the world’s

oceans lie in the southern hemisphere, the phase reflects the peak warming in Austral summer. The seasonal cycle of ocean mass has an amplitude and phase of 6.8 ± 0.6 mm and peaks in late September, reflecting the peak discharge of terrestrial water storage in the northern hemisphere. These results are roughly consistent with those of previous studies [e.g., Chambers *et al.*, 2004; Lombard *et al.*, 2007], although the amplitudes of the seasonal cycles are somewhat smaller than previously reported. This may reflect interannual changes in the amplitude of the seasonal cycle. Such variations have been reported by Chen *et al.* [2005] and Ngo-Duc *et al.* [2005], and are clearly visible in the complete altimeter sea level record (<http://sealevel.colorado.edu/>).

[38] Between 2004 and 2006, the observations suggest that much of the nonseasonal variation in MSL can be attributed to the exchange of water mass between oceans and land. During this period, a small gradual decrease in steric sea level was accompanied by a sudden interannual increase in ocean mass. Beginning in late 2004, ocean mass increased more than 4 mm in about 6 months. Several previous studies have suggested interannual fluctuations in ocean mass of this magnitude or larger [Chambers *et al.*, 2000; Willis *et al.*, 2004], but this is the first confirmation of such a signal based on multiple observations.

[39] Despite the short period of the present analysis, these results have important implications for climate. First, from 2004 to the present, steric contributions to sea level rise appear to have been negligible. This is consistent with observations of ocean surface temperature, which show relatively little change in the global average between 2003 and 2006 [Smith and Reynolds, 2005] (<http://lwf.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html>). It is in sharp contrast, however, to historical analyses of thermal expansion over the past decade [Willis *et al.*, 2004] and the past half century [Antonov *et al.*, 2005; Lombard *et al.*, 2005; Ishii *et al.*, 2006]. Although the historical record suggests that multiyear periods of little warming (or even cooling) are not unusual, the present analysis confirms this result with unprecedented accuracy.

[40] The rate of ocean mass increase based on GRACE during the study period is similar to previous estimates based on observed melting of land bound ice, which tend to be around 1 mm/a [Shepherd and Ingham, 2007; Kaser *et al.*, 2006; Rignot and Kanagaratnam, 2006; Velicogna and Wahr, 2006; Chen *et al.*, 2006]. However, most of the 3.5 mm increase seems to have occurred in a 6-month period between late 2004 and early 2005. On the other hand, the inferred estimate (Jason – Argo) implies a much greater rate of ocean mass increase and significant uncertainties in the trend over the GRACE record remain. Until these issues are resolved, the long-term rate of ocean mass increase remains uncertain.

[41] It is important to note that although these three observing systems are complementary, they are not redundant. As noted above, Argo is capable of measuring density changes in the upper ocean only and on timescales of decades or longer, deep steric changes will cause significant contributions to sea level rise [Antonov *et al.*, 2005]. In addition, the three independent observing systems provide a critical means of cross validation. Such comparisons of independent data sets have helped to detect biases and drifts

in altimeter data [e.g., Mitchum, 1998; Chambers *et al.*, 2003] as well as in situ data (Willis *et al.*, submitted manuscript, 2007), and further intercalibration is clearly needed to determine the cause of the remaining discrepancy in the sea level budget.

[42] **Acknowledgments.** The float data were collected and made freely available by the International Argo Project (a pilot program of the Global Ocean Observing System) and contributing national programs (<http://www.argo.net/>). GRACE and Jason-1 data are from Physical Oceanography Data Archive Center at Jet Propulsion Laboratory, California Institute of Technology. This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA) and via a grant from the NASA Interdisciplinary Science Sponsored Research program to the University of Colorado and the University of Texas.

References

- Antonov, J. I., S. Levitus, and T. P. Boyer (2005), Thermosteric sea level rise, 1955–2003, *Geophys. Res. Lett.*, **32**, L12602, doi:10.1029/2005GL023112.
- Bettadpur, S. (2007), Level-2 gravity field product user handbook, *CSR Publ. GR-03-01 Rev 2.3*, 19 pp., Univ. of Tex. at Austin, Austin.
- Bretherton, F., R. Davis, and C. Fandry (1976), A technique for objective analysis and design of oceanographic experiments applied to MODE-73, *Deep Sea Res. Oceanogr. Abstr.*, **23**, 559–582, doi:10.1016/0011-7471(76)90001-2.
- Chambers, D. P. (2006a), Observing seasonal steric sea level variations with GRACE and satellite altimetry, *J. Geophys. Res.*, **111**, C03010, doi:10.1029/2005JC002914.
- Chambers, D. P. (2006b), Evaluation of new GRACE time-variable gravity data over the ocean, *Geophys. Res. Lett.*, **33**, L17603, doi:10.1029/2006GL027296.
- Chambers, D. P., J. L. Chen, R. S. Nerem, and B. D. Tapley (2000), Interannual sea level change and the Earth's water mass budget, *Geophys. Res. Lett.*, **27**, 3073–3076, doi:10.1029/2000GL011595.
- Chambers, D. P., S. A. Hayes, J. C. Ries, and T. J. Urban (2003), New TOPEX sea state bias models and their effect on global mean sea level, *J. Geophys. Res.*, **108**(C10), 3305, doi:10.1029/2003JC001839.
- Chambers, D. P., J. Wahr, and R. S. Nerem (2004), Preliminary observations of global ocean mass variations with GRACE, *Geophys. Res. Lett.*, **31**, L13310, doi:10.1029/2004GL020461.
- Chambers, D. P., M. Tamisiea, R. S. Nerem, and J. Ries (2007), Effects of ice melting on GRACE observations of ocean mass trends, *Geophys. Res. Lett.*, **34**, L05610, doi:10.1029/2006GL029171.
- Chen, J. L., C. R. Wilson, B. D. Tapley, J. S. Famiglietti, and M. Rodell (2005), Seasonal global mean sea level change from satellite altimeter, GRACE, and geophysical models, *J. Geod.*, **79**, 532–539, doi:10.1007/s00190-005-0005-9.
- Chen, J. L., C. R. Wilson, and B. D. Tapley (2006), Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet, *Science*, **313**, 1958–1960, doi:10.1126/science.1129007.
- Cheng, M., and B. D. Tapley (2004), Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, **109**, B09402, doi:10.1029/2004JB003028.
- Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, **33**, L01602, doi:10.1029/2005GL024826.
- Douglas, B. C., and W. R. Peltier (2002), The puzzle of global sea-level rise, *Phys. Today*, **55**(3), 35–40, doi:10.1063/1.1472392.
- Flechtner, F. (2007), AOD1B product description document for product releases 01 to 04, *GR-GFZ-AOD-0001 Rev. 3.1*, 43 pp., Univ. of Tex. at Austin, Austin.
- Gouretski, V. V., and K. P. Koltermann (2004), WOCE global hydrographic climatology [CD-ROM], *Ber. Bundesamt Seeschiffahrt Hydrogr. Rep.* **35**, 52 pp., Bundesamt Seeschiffahrt Hydrogr., Hamburg, Germany.
- Intergovernmental Panel on Climate Change (2007a), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, U. K.
- Intergovernmental Panel on Climate Change (2007b), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, U. K.
- Ishii, M., M. Kimoto, K. Sakamoto, and S. I. Iwasaki (2006), Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses, *J. Oceanogr.*, **62**, 155–170, doi:10.1007/s10872-006-0041-y.

- Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004, *Geophys. Res. Lett.*, *33*, L19501, doi:10.1029/2006GL027511.
- Leuliette, E. W., R. S. Nerem, and G. T. Mitchum (2004), Calibration of TOPEX/POSEIDON and Jason altimeter data to construct a continuous record of mean sea level change, *Mar. Geod.*, *27*, 79–94, doi:10.1080/01490410490465193.
- Lombard, A., A. Cazenave, P.-Y. Le Traon, and M. Ishii (2005), Contribution of thermal expansion to present-day sea-level change revisited, *Global Planet. Change*, *47*, 1–16, doi:10.1016/j.gloplacha.2004.11.016.
- Lombard, A., D. Garcia, G. Ramillien, A. Cazenave, R. Biancale, J. M. Lemoine, F. Flechtner, R. Schmidt, and M. Ishii (2007), Estimation of steric sea level variations from combined GRACE and Jason-1 data, *Earth Planet. Sci. Lett.*, *254*, 194–202, doi:10.1016/j.epsl.2006.11.035.
- 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.
- Mitchum, G. T. (1998), Monitoring the stability of satellite altimeters with tide gauges, *J. Atmos. Oceanic Technol.*, *15*, 721–730, doi:10.1175/1520-0426(1998)015<0721:MTSOSA>2.0.CO;2.
- Morison, J., J. Wahr, R. Kwok, and C. Peralta-Ferriz (2007), Recent trends in Arctic Ocean mass redistribution revealed by GRACE, *Geophys. Res. Lett.*, *34*, L07602, doi:10.1029/2006GL029016.
- Ngo-Duc, T., K. Laval, J. Polcher, and A. Cazenave (2005), Contribution of continental water to sea level variations during the 1997–1998 El Niño–Southern Oscillation event: Comparison between Atmospheric Model Intercomparison Project simulations and TOPEX/POSEIDON satellite data, *J. Geophys. Res.*, *110*, D09103, doi:10.1029/2004JD004940.
- Paulson, A., S. J. Zhong, and J. Wahr (2007), Inference of mantle viscosity from GRACE and relative sea level data, *Geophys. J. Int.*, *171*, 497–508.
- Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C. J. Somerville (2007), Recent climate observations compared to projections, *Science*, *316*, 709, doi:10.1126/science.1136843.
- Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland Ice Sheet, *Science*, *311*, 986–990, doi:10.1126/science.1121381.
- Shepherd, A., and D. Wingham (2007), Recent sea-level contributions of the Antarctic and Greenland Ice Sheets, *Science*, *315*, 1529–1532, doi:10.1126/science.1136776.
- Smith, T. M., and R. W. Reynolds (2005), A global merged land air and sea surface temperature reconstruction based on historical observations (1880–1997), *J. Clim.*, *18*, 2021–2036, doi:10.1175/JCLI3362.1.
- Swenson, S. C., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*, L08402, doi:10.1029/2005GL025285.
- Swenson, S. C., D. P. Chambers, and J. Wahr (2008), Estimating geocenter variations from a combination of GRACE and ocean model output, *J. Geophys. Res.*, doi:10.1029/2007JB005338, in press.
- Velicogna, I., and J. Wahr (2006), Acceleration of Greenland ice mass loss in spring 2004, *Nature*, *443*, 329–331, doi:10.1038/nature05168.
- Wahr, J., M. Molenaar, and F. Bryan (1998), Time-variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, *103*, 30,205–30,229, doi:10.1029/98JB02844.
- Willis, J. K., D. Roemmich, and B. Cornuelle (2004), Interannual variability in upper ocean heat content, temperature, and thermocline expansion on global scales, *J. Geophys. Res.*, *109*, C12036, doi:10.1029/2003JC002260.
- Willis, J. K., J. M. Lyman, G. C. Johnson, and J. Gilson (2007), Correction to “Recent cooling in the upper ocean,” *Geophys. Res. Lett.*, *34*, L16601, doi:10.1029/2007GL030323.

D. P. Chambers, Center for Space Research, University of Texas at Austin, Austin, TX 78759, USA.

R. S. Nerem, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, Cooperative Institute for Research in Environmental Science, University of Colorado at Boulder, Boulder, CO 80309, USA.

J. K. Willis, NASA/Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove, M/S 300-323, Pasadena, CA 91109, USA. (joshua.k.willis@jpl.nasa.gov)