The Budget of Recent Global Sea Level Rise
2005–2013

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

Date: September 2014

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U.S. Department of Commerce
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Revised 30 September 2014

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Introduction

For decadal and longer time scales, global mean sea level change results from two major processes that alter the total volume of the ocean. Changes in the total heat content and salinity produce density (steric) changes. The exchange of water between the oceans and other reservoirs (glaciers, ice caps, and ice sheets, and other land water reservoirs) results in mass variations. With sufficient observations of sea level, ocean temperatures and salinity, and either land reservoirs or ocean mass, the total budget of global mean sea level can in principle be closed. Expressed in terms of globally-averaged height, contributions to the total budget of global mean sea level are

$$SL_{total} = SL_{steric} + SL_{mass}, \qquad (1)$$

where SL_{total} is total sea level, SL_{steric} is the steric component of sea level, and SL_{mass} is the ocean mass component.

Until recently, efforts to close the sea level rise budget depended in some part on non-global datasets [Church et al., 2011]. While satellite radar altimeters have provided global observations of SL_{total} since the early 1990s, only since 2002 have satellite gravity observations allowed for global estimates of SL_{mass} and not until 2007 had the Argo Project achieved its goal of 3000 floats monitoring SL_{steric}. Now that all three observations have achieved global or near-global coverage, a complete assessment of the sea level budget is possible.

This analysis of the sea level rise budget for the period January 2005 to December 2013 uses corrected Jason-1 and Jason-2 altimetry observations of total sea level, improved upper ocean steric sea level from the Argo array, and ocean mass variations inferred from GRACE gravity mission observations. We demonstrate that the sea level rise budget can be closed, providing verification that the altimeters, Argo array, and GRACE mission produce consistent data.

1 Components of sea level

1.1 Total sea level

For our analysis of SL_{total} from Jason-1 and Jason-2 altimeter data, we use the Radar Altimeter Database System (RADS; http://rads.tudelft.nl/) to extract sea surface height anomalies (GDR-C standards for Jason-1 and GDR-D for Jason-2) with a MOG2D model-based inverse barometer response removed. To account for the effects of glacial-isostatic adjustment (GIA), Earth's viscoelastic response to past ice mass variability, we remove a time-varying geoid predicted with the ICE-5G (VM2) model, which is equivalent to an increase of 0.32 mm/yr of SLR when averaged over the Jason coverage area [Peltier, 2009]. GIA is the response of the solid earth and oceans to past changes in the ice sheets, largely due to the slow viscous response of the Earth's mantle as it rebounds after the disappearance of the giant ice sheets from the last ice age. This process involves a variety of changes in the Earth's crust, rotational axis, and gravity field, as explained in detail in Tamisiea and Mitrovica [2011].

We test a budget closure by substituting an alternative tide model and orbit. The RADS default tide model is the TOPEX-based GOT4.8, but we also use GOT4.10c, which based on Jason data only and includes an adjustment for geocenter motion [Ray, 2013]. It has shown better agreement with bottom pressure gauges in all major tidal constituents [Ray, personal communication]. We also replace the orbits with GSFC std1204 orbits [Lemoine et al., 2010], which employ an ITRF-2008 reference frame and a low-degree (4x4) time-varying gravity field estimated from SLR and DORIS tracking data from up to 11 satellites [Zelensky et al., 2014].

The errors in each 10-day cycle estimate for global mean sea level for Jason-1/Jason-2 are estimated to be 4.0 mm [Leuliette and Scharroo, 2010]. Errors for monthly averages are estimated to be 2.3 mm.

1.2 Steric sea level

To compute SL_{steric} we use monthly objective analyses of quality-controlled ocean temperature and salinity profiles (primarily from Argo) from the University of Hawaii International Pacific Research Center (IRPC, V1.1d), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) [Hosoda et al., 2008], and Scripps Institution of Oceanography (SIO) [Roemmich and Gibson, 2009]. Each data set covers the latitude ranges and depths 0–2000 m. We use the fields from the three centers to compute both the full steric and thermospheric dynamic height variations to 2000m.

The errors in monthly global mean steric sea level range from 3.5 to 2.5 mm for each month, decreasing as Argo coverage increased.

1.3 Ocean mass

For ocean mass variations, we use the GRACE release 5 (RL05) fields available from two processing centers: the University of Texas Center for Space Research (CSR) and GeoForschungsZentrum (GFZ). Each monthly solution consists of Stokes (spherical harmonic) coefficients, C_{lm} and S_{lm}, up to degree and order (l and m) 60. We replace the GRACE C_{20} coefficients with coefficients inferred from satellite laser ranging [Cheng et al., 2013], and we include degree-one coefficients computed as described by Swenson et al. [2008]. To remove an apparent ocean mass signal attributable to GIA we use model results from A et al. [2014].

Standard GRACE processing removes the effects of atmospheric and oceanic variability before constructing a gravity field solution with each center using the same atmospheric and oceanic models. To use GRACE to study the ocean, these model predictions need to be added back to the solutions. Each center provides monthly averages of the gravity field contributions from the ocean model, and we add those averages back to the GRACE gravity field solutions before our processing, so that our GRACE estimates reflect the total mass signal. The bottom pressure at any location includes the weight of the overlying atmosphere, in addition to that of the ocean. By adding back the ocean model's monthly averages we are also adding back the effects of atmospheric pressure over the ocean. This is effectively equivalent to adding back just the ocean, but after removing the inverted barometer contributions of the ocean's response, consistent with how we remove the IB from the altimetry. Following Johnson and Chambers [2013], we use an unsmoothed kernel to estimate global mean ocean mass changes, and smoothed and scaled maps for deviations in regional trends.

2 Sea level budget

When computing trends from each field or their spatial averages, we simultaneously fit seasonal (once- and twice-per-year) terms with a linear term and a bias. To assess the closure of the budget for each combination of SL_{total}, SL_{mass}, and SL_{steric}, we compute the variance of monthly time series of residuals of the global-averaged $SL_{residual} = SL_{total} - SL_{mass} - SL_{steric}$ after removing the seasonal signal.

Trends and seasonal terms for SL_{mass}, SL_{steric}, and, SL_{total} are determined with a least squares fit of a sine, cosine, trend, and constant over January 2005 to December 2013. No smoothing was performed on the time series. The Argo and GRACE time series are monthly observations. Errors in Table 1 are estimated from the least squares fit, where we have assumed that each sample is an independent measurement.

We evaluated 36 processing combinations, using 3 altimetry, 2 GRACE, and 6 Argo processing strategies of SL_{steric} to 2000 m. The variance of the residuals in the 36 $SL_{residual}$ ranges from 4.0 to 6.8 mm^2. The trends in the residuals range from -0.15 mm/yr to 0.23 mm/yr. Table 1 and Figure 1 illustrate the degree of closure that is best achieved with the combination with the lowest variance, which use the SIO grids for SL_{steric}, CSR GRACE fields for SL_{mass}, and the new tides and orbits for SL_{total}.

As spatial distribution of the trends in SL_{total} from Jason-1 and Jason-2 closely resembles the distribution from the combination of steric sea level and ocean mass (Figure 2), as has been noted previously [e.g. Leuliette and Willis, 2011]. When plotted on the same scale as the SL_{total} and SL_{steric}, the spatial distribution of the trends in SL_{mass} from the RL05 CSR GRACE fields in terms of equivalent sea level appears to be nearly uniform, around 2 mm/year (Figure 3). Local deviations range from 1 to 3 mm/yr, presumably reflecting ocean mass redistributions while some of the largest signals are from geoid changes associated with large earthquakes (e.g. Sumatra-Andaman 2004) and signal leakage from glacier and ice sheet melt.

In this analysis, the global sea level rise budget for 2005–2013 is closed . The sum of steric sea level rise and the ocean mass component has a trend of 2.8 to 3.1 ± 0.5 mm/a over the period, depending on the steric sea level dataset used. The rate is consistent with total sea level rise observed by Jason-1 and Jason-2 (3.0 ± 0.4 mm/a) within a 95% confidence interval. These rates represent the globally averaged changes in sea level and have magnitudes on the order of millimeters per year. The regional patterns of sea level change, however, are many times larger and can be extremely complex. Steric sea level change is the dominant contributor to the spatial trend patterns observed for total sea level (Figures 2 and 3).

Table 1. Sea level rise budget for January 2005 to December 2013

	Trend (mm/year)
Ocean mass (GRACE CSR, A et al. GIA)	2.0 ± 0.2
Steric (0–2000m)	0.8 to 1.1 ± 0.5
Steric + mass	2.8 to 3.1 ± 0.5
Total sea level (Jason-1 and Jason-2)	3.0 ± 0.4

Determined with a least squares fit of a sine, cosine, trend, and constant. The error bounds represent the 95% confidence interval obtained from the least squares fit.

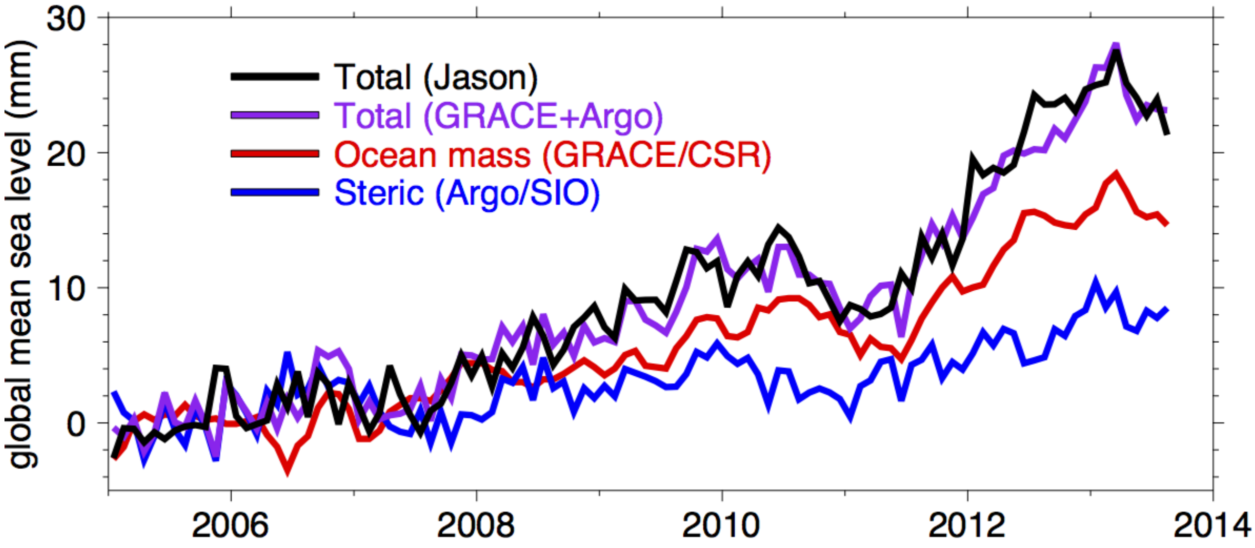

Figure 1. Monthly estimates from Jason-1 and Jason-2 of global mean sea level (black), which are in general agreement with the sum (purple) of the ocean mass component from the Gravity Recovery and Climate Experiment, GRACE (red), and the steric component of the upper 2000 m from Argo (blue). Seasonal signals have been removed. No smoothing has been applied. We have used processing which provides the best closure: Argo (SIO), GRACE (CSR), and Jason with time varying-gravity and GOT4.10 tides.

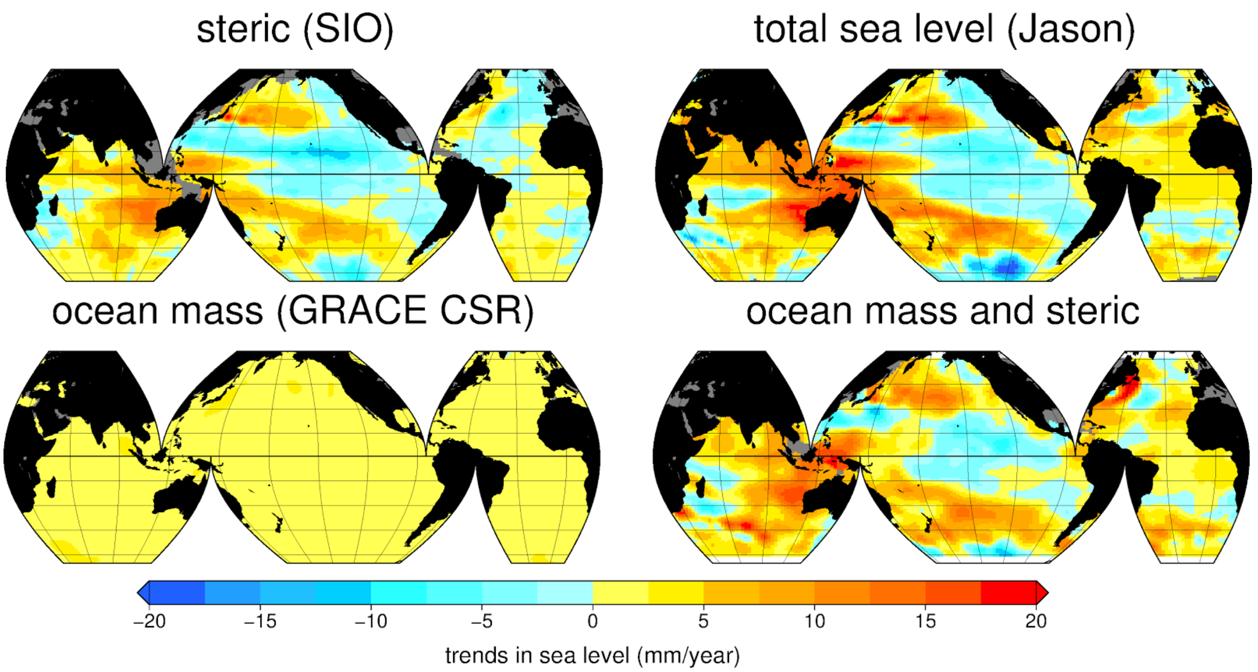

Figure 2. Trends from January 2005 through December 2013 in steric sea level from Argo (top left) ocean mass from CSR GRACE fields in terms of equivalent sea level (bottom left), total sea level from Jason-1 and Jason-2 (top right), and total sea level from adding Argo and GRACE (bottom right).

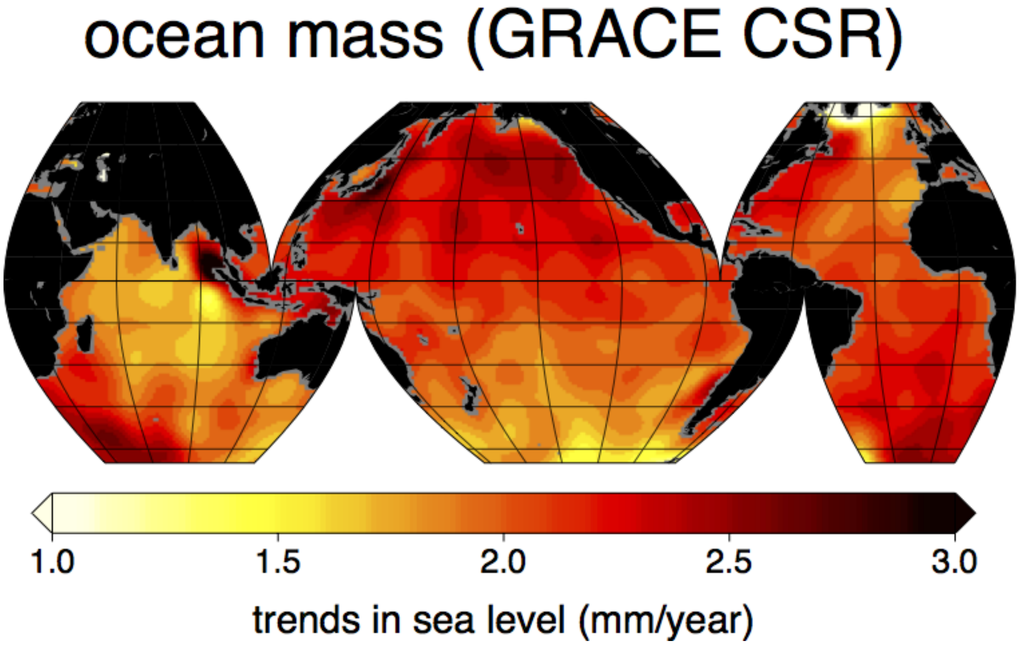

Figure 3. Trends in ocean mass from January 2005 through December 2013 from the CSR RL05 GRACE fields in terms of equivalent sea level (same as in Fig. 4, but using a different color scale).

Acknowledgments

The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official NOAA or U.S. Government position, policy, or decision. The GRACE data are available at http://podaac.jpl.nasa.gov/grace. We thank Geruo A for providing GIA corrections to the GRACE data. The altimeter data can be downloaded from http://rads.tudelft.nl/. We thank R. Ray for providing the GOT4.10 tide model. The figures were produced with the Generic Mapping Tools [Wessel et al., 2013].

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