The Budget of Recent Global Sea Level Rise

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1. 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

$$SL_{total} = SL_{steric} + SL_{mass}, \tag{1}$$

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 [Bindo□ et al., 2007]. 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.

An analysis of the budget by Lombard et al. [2007] for August 2002 to April 2006 using sea level data from GRACE (Gravity Recovery and Climate Experiment), and in situ steric measurements is not able to close (1). Willis et al. [2008] present an analysis of the budget from Jason-1 measurements of sea surface height, SL_{steric} from ocean temperature and salinity data from Argo profiling floats, and SL_{mass} from time-variable gravity from the CSR (Center for Space Research) Release 4 version of GRACE and satellite laser ranging observations between mid-2003 and mid-2007. They find that the resulting four-year trends do not close the budget and suggest that systematic long-period errors may remain in one or more of the observing systems.

Leuliette and Miller [2009] compare their steric estimate to that of Willis et al. [2008] and see significant differences prior to 2005, which they speculate are due to poor sampling in the earlier Argo data and the different climatologies used to estimate the anomalies. Cazenave et al. [2008] estimate a significantly higher GRACE mass rate than Willis et al. [2008] or Leuliette and Miller [2009] based on a post-glacial rebound adjustment of 2 mm/yr (Peltier 2009), which is twice the value of other studies.

Our new analysis of the sea level rise budget for the period January 2004 to March 2010 uses corrected Jason-1, Jason-2, and Envisat 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 are providing consistent data.

1 Components of sea level

1.1 Total sea level

Variations in total sea level used in this analysis came from altimetry data from the Jason-1, Jason-2, and Envisat missions processed using the Radar Altimeter Database System (RADS, http://rads.tudelft.nl/). All sea surface height estimates remove the GOT4.7 tide model and a MOG2D model-based inverse barometer.

Jason-1 was moved to an orbit interleaved with Jason-2 in January 2009. In this study, we construct a Jason-1/Jason-2 monthly time series by combining Jason-1 data from January 2004 to June 2008 (cycles 73 to 243) and Jason-2 data from July 2008 to March 2010 (cycles 1 to 65). The Jason-1 data in RADS are largely based on Geophysical Data Records (GDR) version C, and the Jason-2 data are derived from GDRs.

To determine SL_{total}, maps are first created for each cycle by averaging all individual sea surface heights that are greater than 200 km from the nearest coast into 2° x 1° bins. An area-weighted mean is made from each map, using a mask that excludes areas with >50% ice coverage to avoid aliasing of the seasonal signal. To account for the effects of glacial isostatic adjustment (GIA), we add a +0.3 mm/a trend [Douglas and Peltier, 2002; Peltier, 2009].

Sea level rise trend estimates from altimetry can be independently verified using a network of tide gauges [Mitchum, 2000; Leuliette et al., 2004]. Tide gauge calibrations for the period 2004 to 2010.25 show that the drifts in Jason-1 (–0.1 ± 0.5 mm/a) and Jason-2 (+#.# ± 0.5 mm/a) are both consistent with zero trend. Based on the tide gauge calibration, 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.

1.2 Steric sea level

The Argo Project is a global array of free-drifting profiling floats that measures the temperature and salinity of the upper layer of the ocean. We use in situ temperature and salinity profiles from the Argo floats to estimate changes in ocean density. Only Argo profiles with both salinity and temperature measurements are included. We use data available from the National Oceanographic Data Center on 29 June 2010, discarding all profiles from so-called greylisted instruments with erroneous pressure values [Willis et al., 2009]. Delayed-mode data are used where available, Argo quality control flags are used to eliminate spurious measurements, and profiles from marginal and inland seas are excluded. While most Argo profiles reach at least 1500 m depth, the tropics lack sufficient coverage at that level. To determine SL_{steric}, we integrate ocean density to a depth of 900 m.

Argo deployments began in 2000 and in November 2007 the planned deployment of 3000 floats was achieved. In particular, Argo has dramatically improved coverage of the Southern Hemisphere. In January 2004, the array averaged one profile for each 61,800 km^2 in the Northern Hemisphere and one profile for each 169,700 km^2 in the Southern Hemisphere. By December 2007 the array averages fell to 27,800 km^2 and 41,300 km^2, respectively. We used Argo profile locations to sample the historical altimetry record and concluded that the coverage of the Southern Hemisphere by the Argo array prior to January 2004 is insufficient for closing the sea level rise budget.

Steric height at the location of each profile is also computed from the WOCE gridded hydrographic climatology (WGHC) [Gouretski and Koltermann, 2004]. These WGHC steric heights are then subtracted from the Argo observed steric heights and the resulting anomalies are divided into 5° x 5° horizontal boxes. A standard deviation check is performed in each box, and steric heights more than three standard deviations away from the box mean are removed. Approximately 0.7% of profiles are eliminated with this procedure. After quality control, about ###,### profiles remain between January 2004 and March 2010. Using the steric height anomalies, we create monthly maps of SL_{steric} variability. As in the work by Willis et al. [2008], the maps are created using objective interpolation with a covariance function that 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.

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

Satellite measurements of Earth's time-varying gravity field provided by GRACE are used to infer movement of water mass over Earth's surface. We use Release-04 gravity field solutions from the University of Texas Center for Space Research. GRACE does not observe geocenter variations and current GRACE solutions for oblateness variations may be less accurate than satellite laser ranging (SLR) estimates [Chen and Wilson, 2008]. Therefore, we compute ocean mass variations by replacing the degree 2, order 0 coefficients with those from an SLR analysis [Cheng and Tapley, 2004] and adding an estimate of seasonal geocenter motion [Chen et al., 1999] to account for the degree 1 components of the gravity field. Recent estimates based on ocean models and GRACE fields over land suggest that trends in ocean mass from geocenter variations are on the order of a few tenths of a mm/a [Swenson et al., 2008]. We restore the atmosphere and ocean models removed from the gravity field prior to processing. To compute the equivalent sea level of ocean mass variations that can be compared to SL_{total} as measured by altimetry with an inverse barometer applied, we remove the time-varying mass of the atmosphere averaged over the global ocean.

Secular geoid variations over the ocean that result from GIA must be removed from gravity observations to isolate ocean mass variations. We apply a model [Paulson et al., 2007] that effectively increases the trend in observed SL_{mass} by 1 mm/a. The ice history (ICE-5G) used to produce the GIA model has an estimated uncertainty of roughly 20%.

An averaging function is applied to the GRACE fields that restricts our analysis to the latitudes covered by Jason-1 (± 66°) and excludes regions within 300 km of the continental coastlines. Mass variations in the ocean estimated from satellite gravity observations are vulnerable to leakage of gravity signals from land hydrology. Chambers et al. [2007] suggest that this could cause the secular trend in ocean mass to be underestimated by 0.17 ± 0.08 mm/a. To minimize the sum of the variance from GRACE errors and the variance of signals outside the ocean, we apply a 300-km Gaussian averaging kernel [Wahr et al., 1998]. Errors in the estimated monthly mass component of the global mean sea level are 2 mm for each month [Willis et al., 2008].

2 Sea level budget

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 2004 to March 2010. No smoothing was performed on the time series. The Argo and GRACE time series are monthly observations (N = 63). The altimetry observations of global mean sea level are averaged over the exact repeat cycles (Jason-1/2, 10 days, N = 198). Errors in Table 1 are estimated from the least squares fit, where we have assumed that each sample is an independent measurement.

In this analysis, the global sea level rise budget for 2004–2010.25 is closed when the Paulson GIA correction is applied (Table 1). The sum of steric sea level rise and the ocean mass component has a trend of 1.5 ± 0.4 mm/a over the period when the Paulson GIA mass correction is applied and 2.4 ± 0.4 mm/a when the Peltier GIA mass correction is applied, both well overlapping total sea level rise observed by Jason-1/2 (1.6 ± 0.8 mm/a) within a 95% confidence interval.

Note that altimetry trends are not truly global because the mask used does not include values near coasts. The Jason-1/Jason-2 trend for the entire region between 66°S and 66°N for 2005–2010 is 2.4 mm/year. The Indonesian throughflow, in particular, has seen a large rise during 2005-2010 that significantly changes the trend when it is excluded.

Table 1. Trends and Seasonal Fit for Components of Sea Level Rise and Total Sea Level as Measured by Altimeter

	Trend (mm/year)
Steric (Argo)	0.6 ± 0.4
Mass (GRACE, Paulson GIA)	0.9 ± 0.3
Mass (GRACE, Peltier GIA)	1.8 ± 0.3
Steric + mass (Paulson GIA)	1.5 ± 0.4
Steric + mass (Peltier GIA)	2.4 ± 0.4
Total sea level (Jason-1/2)	1.6 ± 0.8

Determined with a least squares fit of a sine, cosine, trend, and constant over January 2004 to March 2010. The error bounds represent the 95% confidence interval obtained from the least squares fit.

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