Updating the Sea Level Rise Budget, and Its Use as a Calibration Tool

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Abstract

An update to the analysis of Leuliette and Miller [2009] using an additional year (2004 to 2008) of steric and ocean mass components of sea level continues to show that the sea level rise budget can be closed. Here we present five years of corrected and verified Jason-1 and Jason-2 altimetry observations of total sea level, upper ocean steric sea level from the Argo array, and ocean mass variations inferred from GRACE gravity mission observations.

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. As long as concurrent observations are available, closure of the sea level budget can contribute to cross-calibration of the global ocean observing systems.

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

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

where SL_{total} l 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 [Bindoff 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.

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Data analysis

Total sea level from altimetry

Variations in total sea level were processed using Radar Altimeter Database System (http://rads.tudelft.nl/) data from the Jason-1 and Jason-2 missions.

- 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/year trend [Douglas and Peltier, 2002].

Ocean mass from GRACE

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 compute ocean mass variations using RL04 gravity field solutions from the University of Texas Center for Space Research. We replace 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 [Swenson et al. 2008] to account for the degree 1 components of the gravity field. To compare SL_{total} , we restore the atmosphere and ocean models removed from the gravity field prior to processing and remove the time-variable average of atmospheric mass over the ocean.
- Secular geoid variations over the ocean that result from GIA must be removed from gravity observations to isolate ocean mass variations. We apply models [Paulson et al., 2007; Peltier, 2009] that effectively increase the trend in observed SL_{mass} by 1–2 mm/yr.
- Mass variations in the ocean estimated from satellite gravity observations are vulnerable to leakage of gravity signals from land hydrology. To minimize the sum of the variance from GRACE errors and the variance of signals outside the ocean, we exclude regions with 300 km of coasts before applying a 300-km Gaussian averaging kernel.

Steric sea level from Argo

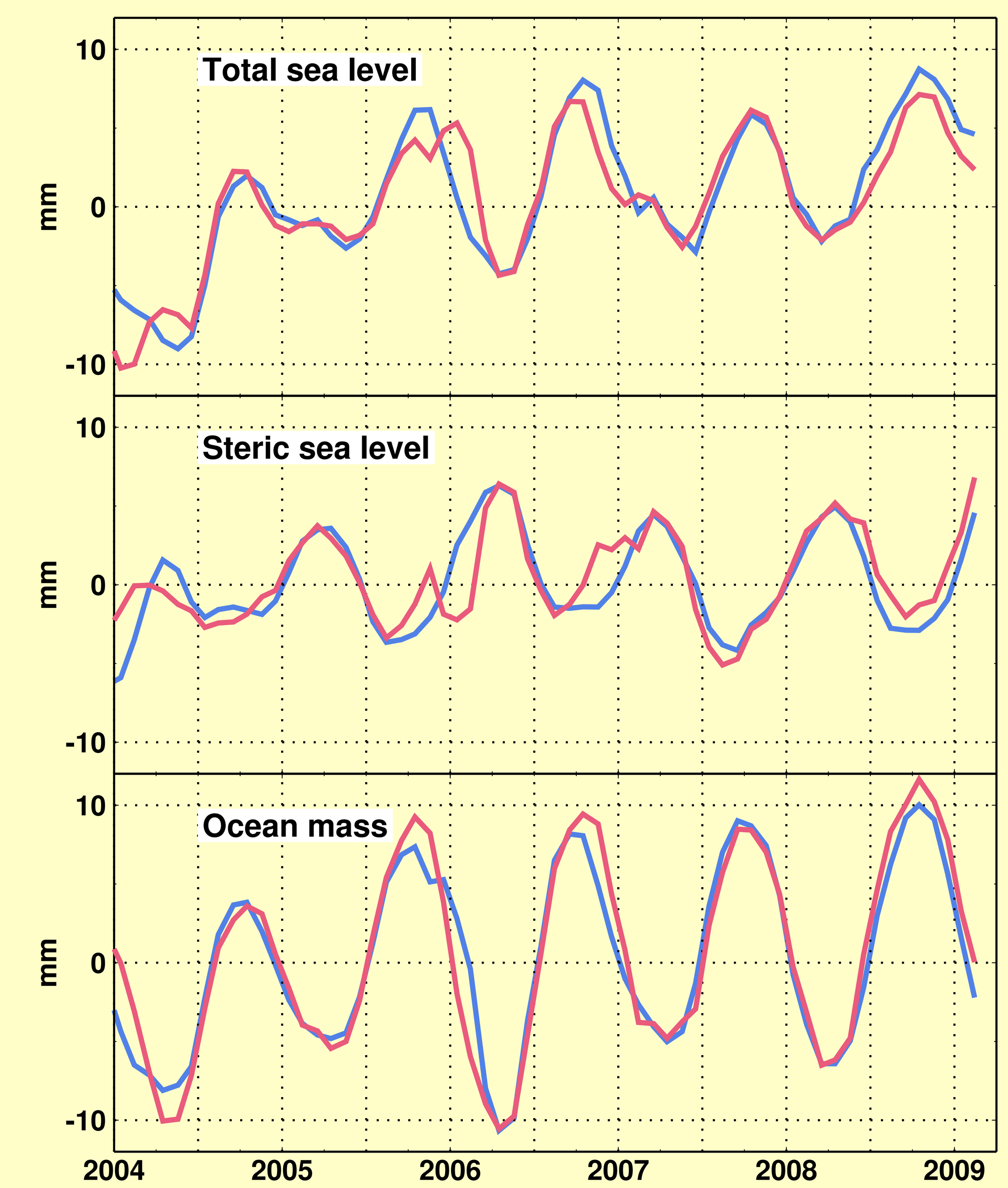
The Argo Project is a global array of free-drifting profiling floats that measures the temperature and salinity of the upper layer of the ocean. We use in situ temperature and salinity profiles from the Argo floats to estimate changes in ocean density.

- While Argo has dramatically improved coverage of the Southern Hemisphere. We used Argo profile locations to sample the historical altimetry record and concludes that the coverage of the Southern Hemisphere by the Argo before January 2004 is insufficient for closing the sea level rise budget.
- Only Argo profiles with both salinity and temperature measurements are included. We use data available from the National Oceanographic Data Center in June 2009, discarding all profiles from greylisted instruments with erroneous pressure values. 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.
- Steric height at the location of each profile is also computed from the WOCE gridded hydrographic climatology (WGHC). These WGHC steric heights are then subtracted from the Argo observed steric heights and the resulting anomalies are divided into 5° × 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.
- Using the steric height anomalies, we create monthly maps of SL_{steric} variability. As in 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.

Results

Sea level rise budget, 2004.0 – 2009.25
(regions > 300 km from coasts)

	Amplitude (mm)	Phase (°)	Trend (mm/year)
Steric (Argo)	3.9 ± 1.6	89 ± 17	0.5 ± 0.5
Mass (GRACE, Paulson GIA)	7.8 ± 1.0	261 ± 5	0.9 ± 0.3
Mass (GRACE, Peltier GIA)			1.8 ± 0.3
Steric + mass (Paulson GIA)	4.0 ± 1.9	254 ± 18	1.4 ± 0.6
Steric + mass (Peltier GIA)			2.3 ± 0.6
Total sea level (Jason-1/2)	4.8 ± 2.5	248 ± 21	1.8 ± 1.1



Variability in total global mean sea level and its steric and mass components. The blue lines are the observed (top) total sea level from Jason-1 and Jason-2, (middle) steric sea level from Argo, and (bottom) ocean mass from GRACE. The red lines show the inferred variability from the complementary observations computed as in (1). A 3-month boxcar smoothing is applied to each time series.

Discussion

- Peltier [2009] and Cazenave et al. [2008] suggest that the GIA correction to the the sea level component from ocean mass variations should be 1.95 mm/year, rather than the Paulson correction of 1.0 mm/year used in Leuliette and Miller [2009]. Peltier did not estimate a correction using a mask that excludes regions within 300 km of coasts, but if we apply the 1.95 mm/year correction to the ocean mass time series, the trend in total sea level from steric+GRACE is 2.3 mm/year. With the Paulson correction, trend in the mass+steric time series is 1.4 mm/year. The trend in the total sea level time series from Jason-1/2 is 1.8 mm/year, and therefore for both GIA corrections the 2004–2009.25 budget is closed to within the estimated errors.
- This analysis uses RADS Jason-1 data based largely on Geophysical Data Records (GDR) version-C' and Jason-2 GDR-T. The Jason-1 data use the complete JMR correction product for the wet troposphere. The drift estimated from a tide gauge calibration of the RADS Jason-1 data (Mitchum, personal communication) is not significant (0.26 ± 0.4 mm/year), but suggests that the total sea level time series may be biased low.