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Closing the sea level rise budget with altimetry, Argo, and GRACE

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[1] An analysis of the steric and ocean mass components of sea level shows that the sea level rise budget for the period January 2004 to December 2007 can be closed. Using corrected and verified Jason-1 and Envisat 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, we find that the sum of steric sea level and the ocean mass component has a trend of 1.5 ± 1.0 mm/a over the period, in agreement with the total sea level rise observed by either Jason-1 (2.4 ± 1.1 mm/a) or Envisat (2.7 ± 1.5 mm/a) within a 95% confidence interval. **Citation:** Leuliette, E. W., and L. Miller (2009), Closing the sea level rise budget with altimetry, Argo, and GRACE, *Geophys. Res. Lett.*, *36*, L04608, doi:10.1029/2008GL036010.

1. Introduction

[2] 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.

[3] 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. An analysis of the budget by *Lombard et al.* [2007] for August 2002 to April 2006 using sea level data from Jason-1 altimetry, time-variable gravity 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.

[4] Our new analysis of the sea level rise budget for the period January 2004 to December 2007 uses corrected Jason-1 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.

2. Data Analysis

2.1. Altimetry

[5] Variations in total sea level used in this analysis came from altimetry data from the Jason-1 and Envisat missions processed using the Radar Altimeter Database System (RADS, http://rads.tudelft.nl/). All sea surface height estimates remove the FES2004 tide model and a MOG2D model-based inverse barometer. The Jason-1 data during 2004–2008 span cycles 73 to 221 and are largely based on Geophysical Data Records (GDR) version B with the exceptions of the wet troposphere path delay corrected for a scale problem (S. Brown, personal communication, 2007) and a sea state bias correction based on the GDR-C model. The Envisat data are from cycles 23 to 65 and use orbits from the Delft Institute for Earth-oriented Space Research (DEOS) using the EIGEN-CG03C gravity model. A dry troposphere path delay correction based on Cartesian ECMWF grids of sea level pressure fixes some artifacts in the correction present in the GDR that is based on Gaussian ECMWF grids of surface pressure. This new correction also removes two jumps present in the GDR, each 0.5 mm and both lengthening the path delay, on 6 June 2005 and 31 January 2006. Recalibrated microwave radiometer brightness temperatures (B. Picard, personal communication, 2008) are applied through cycle 62. For those cycles, a drift correction (+0.156 K/yr) based on an analysis of coldest brightness temperatures is applied to the 23.8 GHz channel. For later cycles, the channel is additionally adjusted upward by +0.154 K. To be consistent with Jason-1 data, we restrict our Envisat observations to latitudes below 66°.

[6] To determine SL_{total}, maps are first created for each cycle by averaging all individual sea surface heights that are

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greater than 200 km from the nearest coast into 2° × 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].

[7] 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 2008 show that the drifts in Jason-1 (−0.1 ± 0.5 mm/a) and Envisat (+0.3 ± 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 are estimated to be 4.0 mm. For each 35-day cycle of Envisat data, the global mean error in SL_{total} is estimated to be 3 mm.

2.2. Argo

[8] 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 9 July 2008, 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.

[9] 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.

[10] 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° × 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 242,305 profiles remain between January 2004 and December 2007. 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.

[11] 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.

2.3. Satellite Gravity

[12] 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.

[13] 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%.

[14] 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].

3. Discussion

[15] 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 December 2007. No smoothing was performed on the time series. The Argo and GRACE time series are monthly observations (N = 48). The altimetry observations of global mean sea level are averaged over the exact repeat cycles (Jason-1, 10 days, N = 147 and Envisat, 35 days, N = 42). Errors in Table 1 are estimated from the least squares fit, where we have assumed that each sample is an independent measurement.

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

	Amplitude (mm)	Phase (deg)	Trend (mm/a)
Steric (Argo)	3.9 ± 1.9	90 ± 19	0.8 ± 0.8
Mass (GRACE)	8.0 ± 1.1	262 ± 5	0.8 ± 0.5
Sum of steric and mass	4.2 ± 2.1	253 ± 20	1.5 ± 1.0
Total sea level (Jason-1)	4.0 ± 1.6	242 ± 16	2.4 ± 1.1
Total sea level (Envisat)	4.4 ± 3.0	230 ± 27	2.7 ± 1.5

[a] Determined with a least squares fit of a sine, cosine, trend, and constant over January 2004 to December 2007. The error bounds represent the 95% confidence interval obtained from the least squares fit.

[16] The out-of-phase nature (Figure 1 and Table 1) of the steric and mass curves has been noted before [*Chambers et al.*, 2004; *Chambers*, 2006; *Chen et al.*, 2005; *Lombard et al.*, 2007; *Willis et al.*, 2008]. The seasonal maximum in SL_{steric} occurs in the late Southern Hemisphere summer when heat storage in the majority of the ocean peaks. For SL_{mass} the seasonal maximum exchange of freshwater from the land and to the ocean is in the late Northern Hemisphere summer. Our analysis of the seasonal budget for the 2004–2008 period (Table 1) shows that the seasonal amplitude and phase in the combined steric and mass time series (4.2 ± 2.1 mm and 253 ± 20°) compare very well with the total global mean sea level results from Jason-1 (4.0 ± 1.6 mm and 242 ± 16°). The comparison with Envisat (4.4 ± 3.0 mm and 230 ± 27°) agrees within the 95% confidence interval, though less well than Jason-1.

[17] In this analysis, the global sea level rise budget for 2004–2008 is closed (Figure 1 and Table 1). The sum of steric sea level rise and the ocean mass component has a trend of 1.5 ± 1.0 mm/a over the period, well overlapping total sea level rise observed by either Jason-1 (2.4 ± 1.1 mm/a) or Envisat (2.7 ± 1.5 mm/a) within a 95% confidence interval.

[18] *Willis et al.* [2008] (hereinafter referred to as WCN08) were unable to close the sea level rise budget using nearly the same methods and data sets used in the present study (LM) for a slightly earlier 4-year interval (2003.5–2007.5). They concluded that one or possibly two of the observing systems could have systematic errors. Given that we get budget closure, it is important that we try to explain why our results are so different. The two most conspicuous discrepancies between the two studies are found in the Jason-1 altimeter total sea level trends and the Argo steric sea level trends. The altimeter trend difference (3.6 mm/a in WCN08 versus 2.4 mm/a for LM) is due to both the half-year offset in sample intervals and the result of different processing techniques, orbits, and tropospheric corrections. Our Jason-1 trend estimate for the 2003.5–2007.5 interval is 3.1 mm/a. The 2004–2008 interval employed in our study was more strongly influenced by La Niña cooling in the Pacific towards the end of 2007, as indicated by a drop in NINO3 SST of 2.78°C between the beginning and end of 2007 (http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices). Hence, there is no reason to suspect a systematic error in the altimeter observations.

[19] The Argo trend differences (−0.5 mm/a for WCN08 versus 0.8 mm/a for LM) are more problematic. Figure 2 shows a comparison of WCN08's Argo steric sea level time series with our analysis extended back to 2003.5. The two records show good agreement between 2005.0 and 2007.5, but differ by as much 6 mm in the 2003.5–2005.0 interval. As described in Section 2.2, in 2003.5 the mean area per Argo profile was approximately six times greater in the Southern Hemisphere than in the Northern Hemisphere. We avoid some, but not all of this period of poor sampling by beginning our analysis in 2004.0.

[20] To check the impact of Argo sampling on their SL_{steric} trend analysis, WCN08 performed an experiment, using Jason-1 data as a proxy for Argo data. Jason-1 data were first interpolated to the time and location of each Argo profile and then monthly maps were computed using the same objective analysis technique used in their Argo analysis. *Willis et al.*, 2008, Figure 5] show a monthly global mean Jason-1 sea level time series computed in this manner compared with one computed from all of the Jason-1 data. WCN08 claim close agreement between the two series, with the sub-sampled data trending lower by 0.4 mm/a (not enough to fully explain the discrepancy in their budget). However, the two curves differ substantially in the 2003.5–2004.5 interval with the fully sampled Jason-1 record lower at times by as much as 4 mm compared to the sub-sampled Jason-1 record.

[21] The similarity between WCN08's Figure 5 and our Figure 2 suggests that poor sampling is at least partly responsible for the steric trend difference between the two studies but it may not be the whole explanation, as both studies use the same raw Argo data. Another possible explanation involves the fact that the two studies used different steric sea level climatologies to compute steric sea

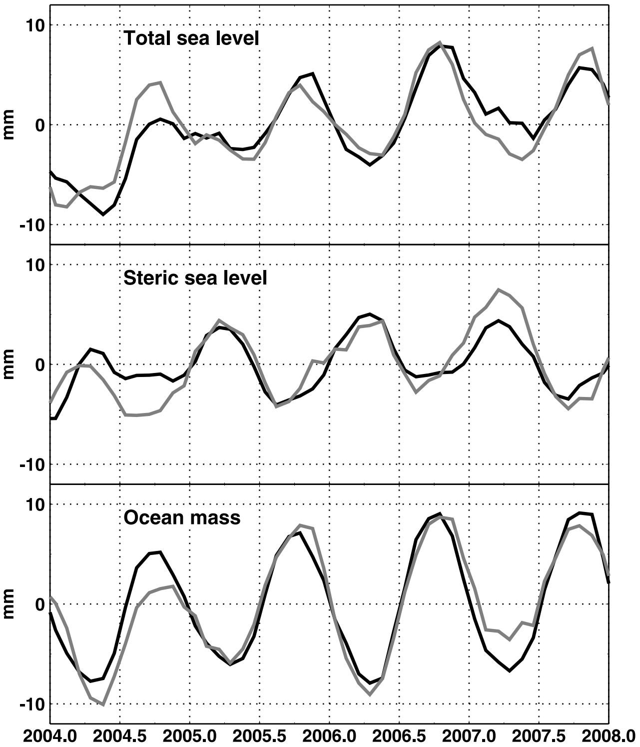

Figure 1. Variability in total global mean sea level and its steric and mass components. The black lines are the observed (top) total sea level from Jason-1, (middle) steric sea level from Argo, and (bottom) ocean mass from GRACE. The gray lines show the inferred variability from the complementary observations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

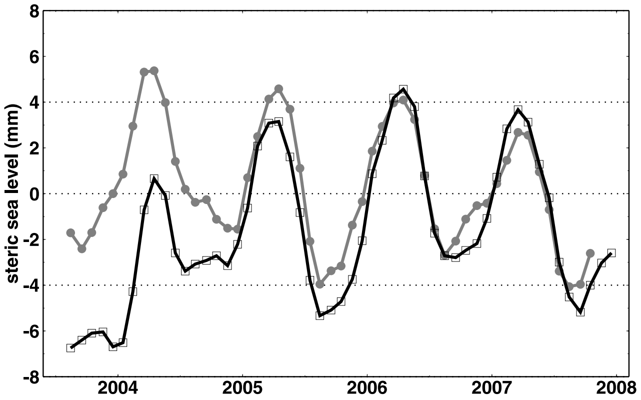

Figure 2. Monthly variations in global mean steric sea level computed by *Willis et al.* [2008] (gray line) and this study (black line). A 3-month boxcar smoothing is applied to each time series.

level anomalies. WCN08 used the time mean computed from all Argo data collected between 2004.5 and 2006.5 to correct the WOCE gridded hydrographic climatology, whereas we used the WGHC for this purpose. If WCN08's Argo climatology is higher than the WGHC in some regions of the Southern Hemisphere, their steric objective analysis may be biased upward in the 2003.5–2005.0 interval due to poor sampling, resulting in an low-biased steric trend estimate over their study interval, 2003.5–2007.5.

4. Conclusions

[22] Regional trends in sea level rise are driven primarily by local variations in steric sea level. During our study period the individual components of sea level experienced weak El Niño conditions in 2004–2005 and 2006–2007 and a moderate La Niña, which began developing in mid-2007. As a consequence, sea level rise (1.5–2.4 mm/a) during the period is 33–50% slower than the rate reported in the 4AR. Most of the sea level rise during 2004–2008 occurred in the Southern Hemisphere (3.1 mm/a) and the rate of sea level rise in the Northern Hemisphere (0.2 mm/a) was the lowest of any four-year period since regular altimetry observations began. In particular, the rate in sea level rise in the Indian ocean observed by altimetry was 4.7 mm/a and 7.4 mm/a from Envisat and Jason-1, respectively. Poor coverage of the Indian ocean prior to 2006 or other systematic errors may affect our analysis with SL_{steric}, which shows a rise of only 2.4 mm/a over the basin.

[23] The recent Fourth Assessment Report (4AR) of the Intergovernmental Panel on Climate Change [*Bindoff et al.*, 2007] concluded that thermal expansion accounts for 23 ± 9% of the observed rate of sea level rise from 1961 to 2003. *Miller and Douglas* [2004, 2006] reached a similar conclusion by comparing steric sea level rise over the past 50 years in three oceanic regions to the observed rise based on tide gauges. For the altimetry era (1993 to 2003) the AR4 reported that the trend in the sum of SL_{steric} and SL_{mass} (2.8 ± 0.7 mm/a) and the trend in SL_{total} observed by TOPEX and Jason-1 (3.1 ± 0.7 mm/a) differed by an amount consistent with zero trend (0.3 ± 1.0 mm/a) within the estimated 90% confidence interval for the observations. The SL_{steric} component accounts for roughly half of the total sea level rise during that period. Our analysis suggests that the proportion of total sea level rise explained by steric component during 2004–2008 is similar to the proportion from 1993 to 2003 — about 40–50%.

[24] While four years is a short period to interpret trends, the excellent agreement in observing systems demonstrates that the global ocean observing systems can be used to close the budget and verify the complementary observations.

[25] **Acknowledgments.** The Argo data were obtained from the Global Argo Data Repository (http://www.nodc.noaa.gov/argo/) maintained by the NOAA National Oceanographic Data Center. The GRACE data were obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) (http://podaac.jpl.nasa.gov/grace/) at the NASA Jet Propulsion Laboratory, Pasadena, CA. We thank G. Mitchum for updated tide gauge calibrations, R. Scharroo for valuable assistance with the RADS database, and W. H. F. Smith and B. Douglas for valuable discussions. We would like to thank D. Chambers and an anonymous reviewer for their helpful suggestions. This investigation was supported in part by the NOAA Office of Climate Observations program and the NASA Ocean Surface Topography program. The views, opinions, and findings contained in this report are those of the authors, and should not be construed as an official NOAA or US Government position, policy, or decision.

References

Bindoff, N. L., et al. (2007), Observations: Oceanic climate change and sea level, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., pp. 385–432, Cambridge Univ. Press, Cambridge, U. K.

Chambers, D. P. (2006), Evaluation of new GRACE time-variable gravity data over the ocean, *Geophys. Res. Lett.*, *33*, L17603, doi:10.1029/2006GL027296.

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. E. Tamisiea, R. S. Nerem, and J. C. 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., and C. R. Wilson (2008), Low degree gravity changes from GRACE, Earth rotation, geophysical models, and satellite laser ranging, *J. Geophys. Res.*, *113*, B06402, doi:10.1029/2007JB005397.

Chen, J. L., C. R. Wilson, R. J. Eanes, and R. S. Nerem (1999), Geophysical interpretation of observed geocenter variations, *J. Geophys. Res.*, *104*(B2), 2683–2690, doi:10.1029/1998JB900019.

Chen, J., C. Wilson, B. Tapley, J. Famiglietti, and M. Rodell (2005), Seasonal global mean sea level change from satellite altimeter, GRACE, and geophysical models, *J. Geod.*, *79*(9), 532–539, doi:10.1007/s00190-005-0005-9.

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.

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.

Gouretski, V. V., and K. P. Koltermann (2004), WOCE global hydrographic climatology [CD-ROM], *Ber. 35*, 52 pp., Bundesamt Seeschiffahrt Hydrogr., Hamburg, Germany.

Leuliette, E., R. Nerem, and G. Mitchum (2004), Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change, *Mar. Geod.*, *27*(1–2), 79–94, doi:10.1080/01490410490465193.

Lombard, A., D. Garcia, G. Ramillien, A. Cazenave, R. Biancale, J. 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*(1–2), 194–202, doi:10.1016/j.epsl.2006.11.035.

Miller, L., and B. C. Douglas (2004), Mass and volume contributions to twentieth-century global sea level rise, *Nature*, *428*(6981), 406–409, doi:10.1038/nature02309.

Miller, L., and B. C. Douglas (2006), On the rate and causes of twentieth century sea-level rise, *Philos. Trans. R. Soc., Ser. A*, *364*(1841), 805–820, doi:10.1098/rsta.2006.1738.

Mitchum, G. T. (2000), An improved calibration of satellite altimetric heights using tide gauge sea levels with adjustment for land motion, *Mar. Geod.*, *23*(3), 145–166, doi:10.1080/01490410050128591.

Paulson, A., S. Zhong, and J. Wahr (2007), Inference of mantle viscosity from GRACE and relative sea level data, *Geophys. J. Int.*, *171*(2), 497–508, doi:10.1111/j.1365-246X.2007.03556.x.

Swenson, S., D. Chambers, and J. Wahr (2008), Estimating geocenter variations from a combination of GRACE and ocean model output, *J. Geophys. Res.*, *113*, B08410, doi:10.1029/2007JB005338.

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*(B12), 30,205–30,230, doi:10.1029/98JB02844.

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.

Willis, J. K., J. M. Lyman, G. C. Johnson, and J. Gilson (2009), In situ data biases and recent ocean heat content variability, *J. Atmos. Oceanic Technol.*, in press.

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