A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits

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Received 13 March 2007; revised 18 May 2007; accepted 29 May 2007; published 28 July 2007.

[1] Mean sea level trends from TOPEX and Jason-1 altimeter data are recomputed using unified geophysical modeling and the new ITRF2005 terrestrial reference frame for the entire altimetric time series, with consistent orbits based on satellite laser ranging (SLR) and DORIS tracking data. We obtain a global rate of 3.36 ± 0.41 mm/yr over the 14 year period from 1993 to 2007. The regional sea level trends computed with the new reference frame show significant north/south hemispherical offsets of ±1.5 mm/yr relative to trends based on the previous 1995-era frame. Regional sea level trend comparisons for the time periods of 1993–1999 and 1999–2005 reveal strong basin-scale polarities and pronounced inter-decadal variability, with a relative increase in the global mean sea level trend of 1.5 ± 0.7 mm/yr in the latter seven years. **Citation:** Beckley, B. D., F. G. Lemoine, S. B. Luthcke, R. D. Ray, and N. P. Zelensky (2007), A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits, *Geophys. Res. Lett.*, *34*, L14608, doi:10.1029/2007GL030002.

1. Introduction

[2] The measurement of mean sea level change from satellite altimetry requires extreme stability of the altimeter measurement system. In particular, the orbit and reference frame within which the altimeter measurements are situated, as well as the associated altimeter corrections, must be stable and accurate enough to permit robust mean sea level (MSL) estimates over an extended time period [*Nerem and Mitchum*, 2001; *Cazenave and Nerem*, 2004]. The most recent analyses [*Leuliette et al.*, 2004; *Nerem et al.*, 2006] from TOPEX/Poseidon (T/P) and Jason-1 data obtain a global MSL rate of 2.8 ± 0.4 mm/yr (without application of correction of −0.3 mm/yr for Global Isostatic Adjustment (GIA)). These analyses used the T/P Geophysical Data Record (GDR) orbits based on the JGM-3 [*Tapley et al.*, 1996] gravity model with the CSR95L02 reference frame [*Eanes*, 1995] through June 2002 (T/P cycle 359) and the ITRF2000 [*Altamimi et al.*, 2002] reference frame after that date. Jason GDR-B orbits were computed using ITRF2000 and GRACE-derived gravity models [e.g., *Picot et al.*, 2003]. *Nerem et al.* [2000] and *Morel and Willis* [2005] previously pointed out, based on simulations, the importance of improvements to the reference frame for sea level determination. In this paper we describe a completely recomputed and consistent time series of all T/P and Jason-1 orbits, based on the new ITRF2005 reference frame [*Altamimi et al.*, 2007], a GRACE-derived geopotential field, and other improvements. We apply updated altimeter corrections, including sea-state bias (SSB) corrections for both TOPEX and Jason-1 (derived using the new ITRF2005-based orbits), and improved water-vapor radiometer corrections for both satellites. In the following sections we summarize the impact of the orbit-modeling improvements on the T/P and Jason orbits, review the changes applied to the altimeter corrections, and then discuss the updated trends in mean sea level.

2. Orbit Improvements

[3] The modeling upgrades include a new GRACE gravity model, GGM02C [*Tapley et al.*, 2005], and the application of time-variable gravity derived from GRACE in the form of annual harmonics to degree and order 20 [*Luthcke et al.*, 2006a]. We forward-model the atmospheric gravity using atmospheric pressure data [*Petrov and Boy*, 2004]. Earth and ocean tide modeling now conforms to IERS2003 standards [*McCarthy and Petit*, 2004], and we apply the GOT00.2 T/P-derived ocean tide model. Our current orbit-determination strategy is compared with the standards used in the T/P GDRs by *Lemoine et al.* [2006]. The new orbits use the ITRF2005 reference frame for the SLR and DORIS station coordinates [*Altamimi et al.*, 2007]. Note that the DORIS station velocities are markedly improved in ITRF2005, since velocities in CSR95L02 were based on very short time series.

[4] The statistics of the TOPEX orbit improvements are summarized in Table 1. The SLR RMS of fit is reduced, as is the independent altimeter crossover RMS. The reduction in variance of the independent altimeter crossovers suggests that the new orbits have a radial accuracy of 1.5 to 2.0 cm, compared with 2.5–3.0 cm for the original TOPEX orbit ephemerides [*Marshall et al.*, 1995; *Lemoine et al.*, 2006].

[5] For Jason we apply an additional correction to mitigate the effects of the geomagnetic South Atlantic Anomaly

Table 1. TOPEX Precision Orbit Determination Results: Cycles 1–364

Orbits	DORIS RMS, mm/s	SLR RMS, cm	Altimeter Crossover RMS,[a] cm
GDR	0.5348	2.21	5.713
ITRF2005	0.5104	1.87	5.472

[a]Altimeter crossover RMS differences shown for 34 selected cycles.

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Table 2. Jason-1 Orbit Determination Summary

Jason SLR/DORIS Cycles 1–177	Average RMS Residuals		
	DORIS, mm/s	SLR, cm	Crossover, cm
ITRF2000 no SAA corr.	0.4078	1.482	5.585
ITRF2000 with SAA corr.	0.3740	1.440	5.578
ITRF2005 with SAA corr.	0.3734	1.423	5.573

(SAA) on the onboard DORIS ultra-stable oscillator [*Willis et al.*, 2004]. The new correction [*Lemoine and Capdeville*, 2006] improves the RMS of fit to the SLR, DORIS, and the (independent) altimeter crossover data (see Table 2) and removes 2.9 mm of radial orbit error in the Jason orbits. We note that even with the application of the SAA correction, the change from the primary to backup DORIS oscillator on Jason caused an apparent radial jump in the orbits of 0.9 mm at Jason cycle 91 (June 2004) which we discern by comparing the SLR/DORIS orbits with those computed using only SLR data and altimeter crossovers.

[6] We evaluated the mean radial orbit differences sampled over the oceans on a cycle-by-cycle basis between our revised orbits and those on the T/P (CSR95L02, JGM3) MGDR_B and Jason-1 (ITRF2000, Eigen-04) GDR-B project GDRs. These orbital differences (shown in Figure 1) will map directly into the global MSL, and they reveal an apparent sinusoidal signature with a period of approximately 11 years with a minimum in 2000. Although taken over 14 years there is a near-zero linear trend, the slope of the leading half-period is −0.44 mm/yr, translating to a reduction in MSL during this time span; the slope of the trailing half-period is +0.44 mm/yr.

[7] In general, the mean radial orbit differences are driven by drifts in the Z coordinate [*Altamimi et al.*, 2007]. We show in Figure 2, the change in the regional MSL rates for TOPEX alone (1993–2002). Although the global average is −0.26 mm/yr (essentially equivalent to the T/P orbital trends), the regional sea level rates at the high northern and southern latitudes show changes of up to ±1.5 mm/yr, clearly a result of the Z-coordinate drifts between the reference frames. Thus, the change in reference frames directly impacts the interpretation of the regional changes in mean sea level. The striping in Figure 2 is the signature of once-per-rev orbit error in the JGM-3 orbits that has been reduced for the new ITRF2005 orbits.

3. Altimeter Correction Improvements

[8] We used the following sets of altimeter data: (1) TOPEX MGDR-B cycles 11–364 (Jan. 1993–Aug. 2002); and (2) Jason-1 GDR-B cycles 1–182 (Jan. 2002–Dec. 2006). All of the standard range and geophysical corrections were applied [*Benada*, 1997; *Picot et al.*, 2003], although a number of additional revisions were introduced to correct instrument-dependent drifts and biases and to ensure inter-mission consistency. Correction for the microwave radiometer drifts is especially critical. The Jason-1 microwave radiometer (JMR) drift is large on the initial GDR-A product, with cm-level offsets over short periods [e.g., *MacMillan et al.*, 2004]; the JMR correction used here follows a recent recalibration by *Brown et al.* [2006a]. The TOPEX microwave radiometer (TMR) correction follows *Brown et al.* [2006b], which corrects for both drift [*Keihm et al.*, 2000] and yaw state biases [*Chambers et al.*, 2003]. In addition, the sea-state bias (SSB) for both TOPEX and Jason-1 is here based on a parametric form [*Gaspar et al.*, 1994], empirically derived from revised crossover sea surface height (SSH) residuals within each cycle with respect to significant wave height and wind speed. The sea-state bias coefficients for TOPEX Alt-A and Alt-B, and Jason GDR-B were estimated separately, as suggested by *Chambers et al.* [2003]. Our SSB analysis employs revised wind speed algorithms specifically tuned to TOPEX [*Gourrion et al.*, 2002] and Jason-1.

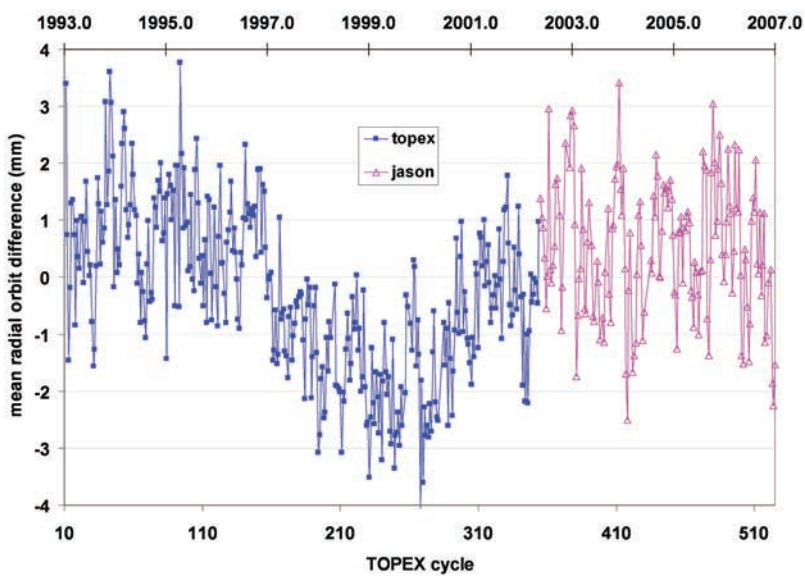

Figure 1. Mean radial orbit differences by cycle, computed between orbits based on ITRF2005 reference frame and GGM02C gravity field and those on the T/P MGDR-B and Jason-1 GDR-B project GDRs. Differences are sampled only over the oceans.

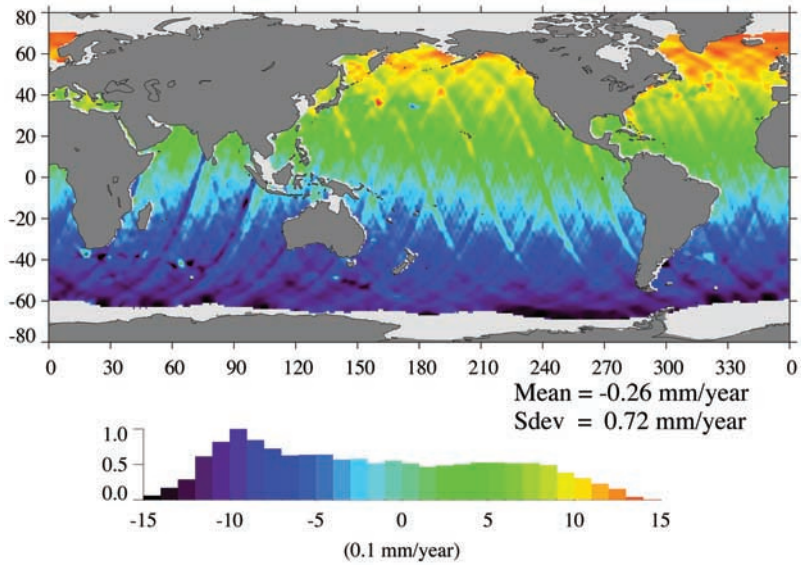

Figure 2. Regional TOPEX (1993–2002) sea surface height (SSH) trend differences from direct impact of ITRF2005 (GGM02C) minus CSR95 (JGM3) orbit differences. The positive values in the Northern Hemisphere indicate a previous underestimation of MSL of up to 1.5 mm/yr in the northwest Atlantic.

[9] A further—and essential—test for drifts in the altimetric systems is performed by comparing the altimetric SSH measurements with those from an array of independent tide gauges [*Mitchum*, 2000]. Our new SSH data have been so compared at 64 tide-gauge sites, courtesy of Prof. Mitchum (Figure 3). The TOPEX versus tide gauge mean height differences have a residual drift of 0.04 mm/yr with a variance of 25 mm^2 about the linear fit; for Jason we obtain 0.69 mm/yr with a variance of 45 mm^2. After adjustment for an intermission instrument bias of 90 mm, as computed from collinear differences during the verification phase, we obtain a combined residual drift of +0.05 mm/yr. The uncertainty in this estimate is ±0.4 mm/yr, which is dominated by systematic error from poorly known vertical land motions at the tide gauges and which does not reduce as the time series lengthens [*Mitchum*, 2000]. This uncertainty therefore also dominates the error budget of our altimeter-derived rates of global mean sea level rise.

4. Global and Regional Mean Sea Level Trends

[10] The technique in computing the global mean SSH variations (Figure 4) follows that of [*Nerem*, 1995] with few modifications. At each 1-sec along-track, geo-registered location, SSH residuals are computed with respect to the local TOPEX mean profile (1993–2002). Ten-day cycle, globally averaged SSH variations are computed with equal-area weighting of observations. Observations are edited with respect to a 200-m ocean depth mask, and a 20-cm mesoscale variability mask. A 60-day Hanning filter is applied to the 10-day averages (black line). A linear trend is fit to the filtered 10-day averages. The linear fit results in a MSL rate of 3.36 ± 0.41 mm/yr over the 14-year time span, which is approximately 0.6 mm/yr higher than earlier estimates of 2.8 ± 0.4 mm/yr by *Leuliette et al.* [2004] and *Cazenave and Nerem* [2004]. However, these earlier studies used a shorter time span, 1993–2003, and had an estimated drift relative to tide gauges of −0.2 mm/yr, suggesting a possible true MSL rate of 3.0 mm/yr. When we limit our time series to the same interval, we obtain 3.07 mm/yr, or 3.02 mm/yr after adjusting by our gauge-based drift of +0.05 mm/yr (Figure 3). The results therefore are very consistent for the shorter time span once our (identical) tide-gauge comparisons are allowed for.

[11] Applying the same procedure to shorter subsets of the sea level time series we obtain 2.53 ± 0.46 mm/yr for the period from 1993 to 2000 (T/P cycles 11 to 268), and 3.99 ± 0.47 mm/yr for the period from 2000 to 2007 (T/P cycle 255 to Jason cycle 182). Thus the global MSL increase over these two 7-year spans is approximately 1.5 ± 0.7 mm/yr. (Note that the contribution of the DORIS oscillator jump at Jason cycle 91 maps into an error in the rate of MSL of 0.19 mm/yr over the current span of the Jason mission (4.9 yrs), but only 0.06 mm/yr over the full T/P + Jason 14-year time span.) Much larger changes in trends over short (decadal) periods have been observed in tide-gauge analyses [e.g., *Douglas*, 1997; *Jevrejeva et al.*, 2006;

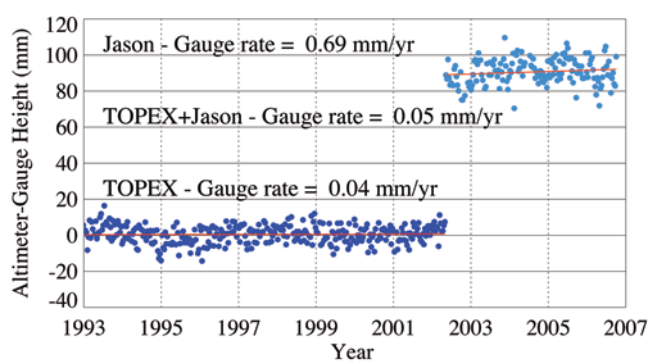

Figure 3. TOPEX and Jason-1 sea surface height mean differences with respect to a 64-site tide-gauge network. The mean TOPEX-Jason instrument bias is consistent with the 90 mm bias, which we estimate from the Feb.–July 2002 calibration campaign data. There is no indication here for an additional offset in our TOPEX Alt-A vs. Alt-B data.

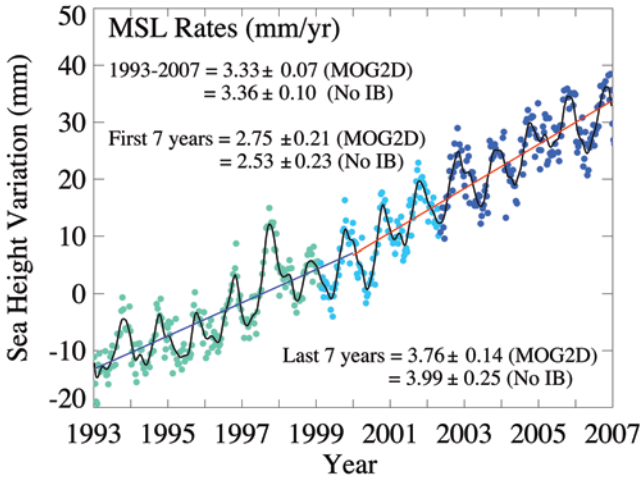

Figure 4. Global mean SSH variations from TOPEX and Jason-1 with respect to 1993–2002 mean, plotted every 10 days. The light green dots represent TOPEX Side A, light blue dots TOPEX Side B, and dark blue dots Jason-1. The solid black line is a 60-day Hanning filter of the altimetric time series. The blue line is a linear fit (estimated simultaneously with seasonal terms) of smoothed SSH variations from 1993 to 2000; the red line is a linear fit from 2000 to 2007. The MSL rates labeled "MOG2D" have SSH adjusted for atmospheric loading effects via the model of *Carrère and Lyard* [2003]. Error estimates shown indicate variance of data about the linear fit, after allowing for serial correlation [*Lee and Lund*, 2004], and should be augmented by the ±0.4 mm/y uncertainty in the altimeter/gauge drift calibration.

Holgate, 2007], although much of that variability must stem from inadequate global coverage. Maps of our regional trend differences (see the auxiliary material)[1] give a global picture of such short-period variability, indicative of "ENSO-like inter-decadal variability" [*Zhang et al.*, 1996], which tends to support the premise that several decades of altimetry may be required to adequately resolve an acceleration term in MSL [*Nerem et al.*, 1999].

[12] Recent glacial ice mass loss determined from the GRACE mission for Greenland (0.43 ± 0.04 mm/yr, updated from *Luthcke et al.* [2006b]) and Antarctica (0.39 ± 0.20 mm/yr [*Velicogna and Wahr*, 2006]) and losses from mountain glaciers such as Alaska (0.32 ± 0.06 mm/yr [*Tamisiea et al.*, 2005]) is presumably contributing to the change in trends we observe over the course of the 14-yr T/P-Jason mission. That ice loss, however, cannot account for the large difference of 1.5 ± 0.7 mm/yr between our first and second 7-yr spans. This further highlights the difficulty of extracting climate-related acceleration terms from short time series, even those, like altimetry, with near-global coverage.

5. Conclusion

[13] We have recomputed global and regional mean sea level trends from TOPEX and Jason-1 altimeter data, using unified geophysical modeling and the ITRF2005 terrestrial reference frame for the entire time series, obtaining a global rate of 3.36 ± 0.41 mm/yr from 1992 to 2007 (without application of a correction for GIA), which is higher than recent determinations that relied on shorter time spans and on orbits computed in different reference frames. The use of the updated gravity field and ITRF2005 frame alters regional MSL rates by up to ±1.5 mm/yr compared with the TOPEX MGDR-B CSR95 frame. Over the entire 14-year span the mean radial orbit differences between the revised orbits and those on the project GDRs map an apparent 11-year near-sinusoidal feature into the GMSL estimates. The effects of changing the reference frame are of the same order as the recent reported mass loss from Greenland or Antarctica, which underscores the importance of efforts to improve the accuracy of the terrestrial reference frame realizations.

[14] **Acknowledgments.** The authors acknowledge the International Laser Ranging Service (ILRS) and the International DORIS Service (IDS) for providing the tracking data for TOPEX/Poseidon and Jason [*Pearlman et al.*, 2002; *Tavernier et al.*, 2006]. Gary Mitchum provided the tide-gauge validation analysis. This research was supported by the NASA Physical Oceanography and EOS/IDS Sea Level programs. We thank Annie Cazenave and Steve Nerem for comments.

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