Improved Determination of Global Mean Sea Level Variations using TOPEX/POSEIDON Altimeter Data

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Improved determination of global mean sea level variations using TOPEX/POSEIDON altimeter data

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Abstract. The TOPEX/POSEIDON satellite altimeter mission has measured sea level on a global basis over the last 4 years at 10 day intervals. After correcting for a recently discovered error in the measurements, the estimated rate of global mean sea level change over this time period is -0.2 mm/year. Comparisons to tide gauge sea levels measured in spatial and temporal proximity to the satellite measurements suggest there is a residual drift in the satellite measurement system of -2.3 ± 1.2 mm/year, the origin of which is presently unknown. Application of this rate correction yields a "calibrated" estimate of +2.1 ± 1.3 mm/year for the rate of sea level rise, which agrees statistically with tide gauge observations of sea level change over the last 50 years. Since the contribution of interannual and decadal mean sea level variations cannot presently be isolated, a longer time series is required before long-term climate change signals can be detected. In addition, an improved understanding of the T/P measurement system performance with time is needed.

Introduction

The U.S./France TOPEX/POSEIDON (T/P) altimeter satellite has been providing global (±66° latitude) maps of sea level change with a point-to-point accuracy of 3-4 cm since its launch on August 10 1992 [*Fu et al.*, 1994]. A number of investigators have reported rates of global mean sea level change using the first 2 years of T/P data [*Rapp et al.*, 1994; *Nerem*, 1995a; *Nerem*, 1995b; *Minster et al.*, 1995]. However, in the absence of an accurate external assessment of the stability of the instrument over time, these results were largely demonstrations of the precision that could be obtained with the T/P data, and little could be concluded about the absolute accuracy of the reported results. Three recent developments now allow us to present a significantly more reliable estimate of global mean sea level rise from the T/P data: 1) an error was recently discovered [*Zanife et al.*, 1996] in the computer software producing the TOPEX data for the mission scientists which effectively increased the apparent observed mean sea level rise by 8 mm/year over 1993-95; 2) increased confidence has been gained in the use of tide gauges to externally calibrate the instrument performance over time [*Mitchum*, 1994; 1997; *Murphy and Moore*, 1996; *Chambers et al.*, 1997], and 3) the span of available T/P data has nearly doubled in length.

Data Analysis

T/P carries two radar altimeters; a NASA dual-frequency altimeter (TOPEX), which operates roughly 90% of the time, and an experimental solid-state single-frequency altimeter (POSEIDON) contributed by CNES, which operates the remaining time. The radar altimeters collect range measurements at a rate of 10 per second, but for this study we used 1-second averages yielding about a half-million measurements every 10 days. These range measurements are combined with a precise orbit ephemeris to compute sea level, which is subsequently corrected for the effects of atmospheric delays, variable sea state, and tidal effects [*Nerem*, 1995b]. Sea level variations caused by variable atmospheric pressure loading are mitigated using the assumption of an inverted barometer response, and for this study are further constrained to have a zero global mean over each 10-day cycle. In addition, we adopted for the TOPEX altimeter ranges calibration corrections derived from on-board internal instrument measurements [*Hayne et al.*, 1994], which show a shortening of the range over 1993-96 of about 1.5 mm/year. After deleting suspect data as described in *Nerem* [1995b], mean sea level variations were computed by averaging the local sea level variations within each 10 day repeat cycle over all observed locations using an equi-area weighting factor computed such that each area of the ocean contributes equally to the mean [*Wang and Rapp*, 1994; *Nerem*, 1995b].

Several unexplained patterns in the T/P data, now recognized as consequences of the software error, emerged over the course of the prime mission. Based on in situ data collected at dedicated verification sites overflown by the satellite, it was determined shortly after launch that the TOPEX altimeter range measurements were too short [*Christensen et al.*, 1994; *Menard et al.*, 1994; *White et al.*, 1994]. A recent estimate of the magnitude of the TOPEX range bias, based on data collected at the NASA prime verification site until just prior to the discovery of the software error, was −125 ± 20 mm [*Haines et al.*, 1996]. Beginning in mid-1995, the measurements of global mean sea level made by the two altimeters started diverging to unacceptable levels (up to a few cm in excess of the initial bias). Increasing disagreement was also observed between tide gauge and TOPEX altimeter sea levels measured in spatial and temporal proximity to one another [*Mitchum*, 1994; 1997]. These disagreements prompted a review of the T/P ground processing software. The aforementioned algorithm error, which was associated with adjustments made

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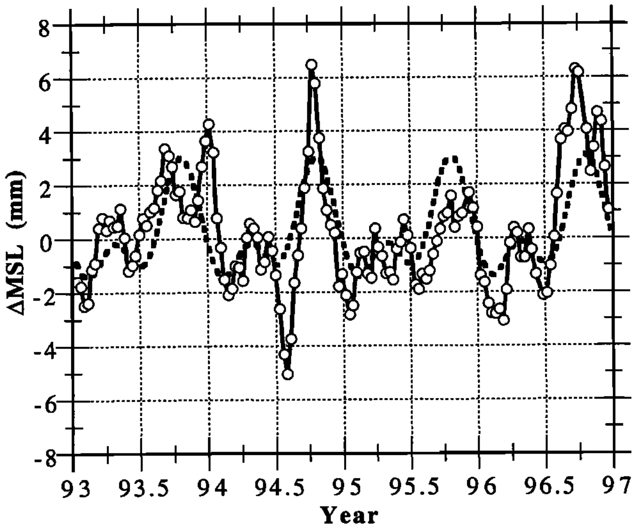

Figure 1. Global mean sea level variations (solid line) computed for each 10-day cycle of T/P altimetry covering Cycles 9-161 (December 11, 1992 - February 5, 1997), and a least squares fit of secular, annual, and semi-annual variations (dashed line). The sea level data have been smoothed using a 60-day boxcar filter.

to the spacecraft clock used to time the radar pulses, was discovered in mid-1996 [*Zanife et al.*, 1996]. In hindsight, the comparison of sea level measurements from tide gauges to nearby T/P sea level measurements did a remarkable job of detecting the erroneous sea level signal in terms of both its variable component [e.g. *Mitchum*, 1997; *Murphy and Moore*, 1996; *Chambers et al.*, 1997] and mean value [e.g., *Haines et al.*, 1996; *Christensen et al.*, 1994; *Menard et al.*, 1994; *White et al.*, 1994]. This experience, along with a recently improved assessment of the inherent errors in the calibration technique [*Mitchum*, 1997], allow us to more confidently use the tide gauges to monitor the performance of the radar altimeter, and correct the measurements if necessary. None of the previously published estimates of global sea level change [*Rapp et al.*, 1994; *Nerem*, 1995a; *Nerem*, 1995b; *Minster et al.*, 1995; *Hendricks et al.*, 1996] were corrected via such an independent external calibration. By "blending" the altimeter and tide gauge data together to determine the sea level rise estimate, this approach represents a significant departure from previous work.

The data set analyzed in this study covers T/P repeat cycles 9 to 161, corresponding to December 11, 1992 to February 5, 1997. Data from the first 80 days of the mission data were eliminated because they are suspect [*Nerem*, 1995b]. After applying a correction to the TOPEX data for the software error [*Hancock and Hayne*, 1996], the previously observed mean bias in the TOPEX altimeter [*Christensen et al.*, 1994; *Haines et al.*, 1996] was reduced to less than 1 cm. The time series of 10-day global mean sea level variations is shown in Fig. 1 after smoothing using a 60-day boxcar filter. Previous investigations have shown these results to be remarkably insensitive to different data editing, measurement correction errors, and satellite orbit errors [*Nerem*, 1995b; *Minster et al.*, 1995]. The trend of the mean sea level variations (determined in a simultaneous least squares fit with annual and semi-annual variations) is -0.2 mm/year, with a scatter (determined from the unsmoothed data) of 0.3 mm/year, 0.5 mm/year after accounting for the autocorrelation of the residuals [*Maul and Martin*, 1993]. Data from the POSEIDON altimeter were included in this trend estimate for completeness, but they had no significant effect on the result. The POSEIDON data alone (Cycles 20-126) produce a trend of -1.4 ± 2.2 mm/year, which is statistically consistent with the TOPEX results.

Data Calibration

The stability of the altimeter instrument calibration is of significant concern for studies of mean sea level change, since the instrument can drift with time as the hardware ages. In addition, external calibration of the measurements is important for identifying a variety of other possible errors, such as the aforementioned software error. The mean instrument biases for T/P, a critical measurement for linking T/P to future altimeter missions, continue to be monitored using tide gauges collocated with a GPS receiver on the Harvest drilling platform located off the coast of Southern California directly under the T/P groundtrack [*Christensen et al.*, 1994]. Current estimates suggest the biases for both TOPEX and POSEIDON are statistically insignificant (< 1 cm). More critical for this study is the drift determination, for which the formal accuracy of the current Harvest estimate is ±3 mm/year. Similar accuracies are being obtained at other regional calibration sites [*White et al.*, 1994; *Morris and Gill*, 1994]. While this level of accuracy is useful for diagnosing potential systematic errors in the measurement systems, the current magnitude of the error precludes applying the drift estimates to the T/P sea level record.

The global tide gauge network, however, can provide an improved estimate of the instrument calibration drift by using many gauges to reduce through averaging the error experienced by a "point" calibration such as Harvest. In short, the TOPEX sea level measurements (there are insufficient measurements at present to reliably monitor the POSEIDON altimeter) in the vicinity of each tide gauge are differenced with the tide gauge sea level measurements. It is critical to understand that application of this technique [e.g., *Mitchum*, 1997] does not imply we are using a global sea level trend inferred from the tide gauges to correct a global sea level trend computed from TOPEX. (For the 4-year time period under consideration for this study, this is in fact precluded by the relatively poor global sampling afforded by the tide gauge network.) Instead, we focus on identifying consistent trends within a global ensemble of local TOPEX minus tide gauge sea level differences. For this purpose it is not necessary that the tide gauges be capable of measuring global sea level directly, but only that they be vertically stable in an ensemble sense for the duration of time spanned by the TOPEX data.

Specifically, there are 149 time series of sea level differences from 53 tide gauges (the nearest four TOPEX passes are used independently at each site). The independence of these time series was carefully checked in the analysis [*Mitchum*, 1994; 1997]. We note, however, that the geographic distribution of the tide gauges favors the tropics. The 149 sea level differences are averaged over each 10 day T/P cycle resulting in a time series of the altimeter instrument behavior. Errors in this time series arise from a number of different sources including: 1) the tide gauges are rarely collocated with the T/P groundtrack, introducing differences in the sea level measured by each technique, 2) ocean waves affect the sea level measurements quite differently (although a sea state correction is applied to the altimeter data), and 3) the land on which the tide gauges are fixed can move, creating an apparent sea level change. The TOPEX minus tide gauge sea level differences that went into the global average at each point in time to form the drift estimate time series were carefully examined for correlations in space and time. Only small correlations were found [*Mitchum*, 1997], and these were accounted for in estimating the errors in the drift estimates. As discussed in detail in [*Mitchum*, 1997], the trend in the TOPEX minus tide gauge sea level differences is -2.3 mm/year with an error of 0.6 mm/year (after accounting for the autocorrelation of the residuals). Although there is evidence that systematic effects are small [*Mitchum*, 1997], allowing an additional ±1 mm/year for the possibility of systematic land motion raises the total error to ±1.2 mm/year. We note this calibration drift estimate will be continually refined during the extended T/P mission, and complementary results from the "point" calibration sites such as Harvest will also become increasingly reliable. These sites are especially valuable because the direct overflight geometries coupled with redundant sensors and ancillary instrumentation allow a reduction in the tide gauge versus altimeter sea level variance well below what is routinely achieved at other tide gauge locations.

It should be noted that this assessment assumes the instrument drift has no geographic dependence. Because the precision of a trend estimate from any single tide gauge is low, it is difficult to assess geographic patterns. There is a suggestion that the tropical gauges have larger patterns, but this result is not statistically significant [*Mitchum*, 1997] and is the subject of ongoing study. If the sensitivity of the microwave radiometer (which provides the correction for the water vapor delay) is changing with time, then one might expect the resultant error to be larger in the tropics where water vapor is more abundant. Because the tide gauges used in the calibration are not distributed globally, and in fact are concentrated more in the tropics, the calibration drift computed from the tide gauges would be biased. If the residual drift in the T/P measurement system is in fact attributable to the microwave radiometer, then the drift estimate of -2.3 mm/year may be biased high by 20-50% [*Mitchum*, 1997]. While this is a large change, it remains within our error estimate.

Results

If we adopt the TOPEX instrument calibration as measured by the tide gauges, then the calibrated rate of sea level rise is +2.1 mm/year. Strictly speaking, the drift estimate should be applied only to the TOPEX altimeter data, as the POSEIDON data were not used in the calibration owing to the small sample size. We note that some components are common to the two altimeter systems, most notably the microwave radiometer, and thus it is possible the POSEIDON data should also be corrected pending a determination of the cause of the observed drift. In any case, the POSEIDON data have only a negligible effect on the sea level rise estimate. Combining the scatter of the sea level rise estimate with the uncertainty of the instrument calibration using the tide gauges, the total uncertainty of this sea level rise estimate is ±1.3 mm/year. We emphasize that the tide gauges cannot by themselves determine a precise value for mean sea level rise over the time period of the T/P mission, since they do not provide sufficient

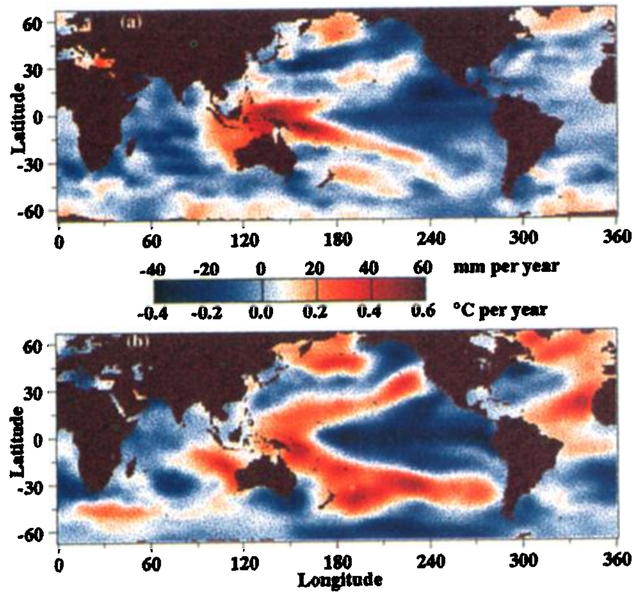

Figure 2. Sea level trends observed by T/P over Cycles 9-161 (a) and sea surface temperature trends [*Reynolds and Smith*, 1994] over the same time period (b). The trend at each location was determined simultaneously with annual and semi-annual sea level variations.

sampling of the global oceans. However, when used for monitoring the altimeter instrument performance, tide gauges are a very powerful tool for calibrating altimeter estimates of sea level change.

Over long time scales, geographic mapping of the sea level rise signal will be very helpful in assessing the cause of the change, since sea level rise resulting from glacier or ice cap melting has a different spatial pattern than sea level rise related to modifications of temperature or salinity. Fig. 2a shows the geographic sea level trends measured by T/P over Cycles 9-161. These trends are highly correlated with their sea surface temperature (SST) counterpart (Fig. 2b), as mapped from in situ and satellite data [*Reynolds and Smith*, 1994]. The correlation coefficient between the two maps is 0.6, with most of the similarities occurring in the Pacific. This would seem to suggest that a significant fraction of the sea level rise is due to heat storage close to the surface of the ocean. We note, however, that the largest sea level (and SST) trends are found in the tropical oceans, and presumably stem from the 1994 ENSO event. In this region, the correlation is due to indirect causes, as the sea level signal in the tropics is due primarily to changes in wind stress, and the accompanying SST signal to the water displacements induced by wind. In view of the short duration of the present T/P time series, this underscores the challenge in separating regional sea level changes induced by changes in the wind stress from those attributable to variations in heat storage or ocean water mass.

A number of other studies of long-term sea level change using the TOPEX data were also affected by the software error, and thus deserve comment here. To lend insight on the spatio-temporal variability that underlies the T/P derived mean sea level rise estimate, an evaluation of the sea level variations using the technique of Empirical Orthogonal Functions (EOFs) can be performed. Immediately prior to the discovery of the software error, EOF analyses revealed that nearly all of the observed rise in mean sea level could be attributed to a single EOF mode related to the ENSO phenomena [*Hendricks et al.*, 1996]. Application of the corrected data greatly reduces the sea level rise observed in this primary mode, but does not alter this salient conclusion, suggesting that interannual variability contributes significantly to our estimate of sea level rise over the past 4 years. We note however that the link between sea level rise and ENSO cannot be established from this result alone, as the EOF modes are purely empirical, and can reflect contributions from multiple phenomena.

A study of changes in global heat storage using the TOPEX data was also affected by the software error. This was studied by regressing in situ estimates of upper ocean heat storage anomalies measured by expendable bathythermographs against TOPEX sea level height anomalies over 1993-1994 [*White and Tai*, 1995]. The resulting coefficients suggested that heat storage anomalies of 0.5-1.5 x 10^9 Watts-sec m^{-2} per cm are associated with RMS sea level variations of 6 cm and greater, nearly an order of magnitude larger than the TOPEX software error. While this error had a negligible effect on local heat storage estimates, it did introduce artificial trends of 0.2-0.3 x 10^9 Watts-sec m^{-2} into Pacific-, Indian-, and global-average ocean heat storage estimates, which were eliminated after the data were corrected. This software error had no effect upon the basic thesis of the study; i.e., that heat storage anomalies inferred from TOPEX altimetry enable the determination of interannual changes in basin- and global-average heat storage anomalies with an accuracy of ± 2 Watts m^{-2} [*White and Tai*, 1995].

Conclusions

The sea level rise estimate of +2.1 ± 1.3 mm/year for the period December 1992 to February 1997 is in good agreement with the most recent estimates derived from decades of tide gauge data, which are all generally close to +1.8 mm/year [*Douglas*, 1995]. However, because the T/P sea level rise estimate spans only 4 years, the influence of interannual and decadal mean sea level variations cannot be ascertained, and thus the underlying change in mean sea level due to long-term climate change cannot be isolated. With the ever lengthening T/P time series, and with the promise of a proposed follow-on satellite to T/P, called "Jason", it is likely that satellite altimetry will provide important constraints to climate change models by early in the next decade.

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References

Chambers, D. P., J. C. Ries, C. K. Shum, and B. D. Tapley, On the use of tide gauges to determine altimeter drift, *J. Geophys. Res.*, in review, 1997.

Christensen, E. J., B. J. Haines, S. J. Keihm, C. S. Morris, R. S. Norman, G. H. Purcell, B. G. Williams, B. C. Wilson, G. H. Born, M. E. Parke, S. K. Gill, C. K. Shum, B. D. Tapley, R. Kolenkiewicz, R. S. Nerem, Calibration of TOPEX/Poseidon at Platform Harvest, *J. Geophys. Res.*, 99(C12), 24465-24486, 1994.

Douglas, B. C., Global Sea Level Change: Determination and Interpretation, *Rev. Geophys.*, Suppl., 1425-1432, 1995.

Fu, L.-L., E. J. Christensen, C. A. Yamarone, M. Lefebvre, Y. Menard, M. Dorrer, and P. Escudier, TOPEX/POSEIDON mission overview, *J. Geophys. Res.*, 99(C12), 24369-24382, 1994.

Haines, B., E. Christensen, R. Norman, M. Parke and G. Born, Altimeter calibrations and geophysical monitoring from collocated measurements at the Harvest platform (abstract), *EOS Trans.*, 77(22) Suppl., W16, 1996.

Hancock, D. W. and G. S. Hayne, http://osb3.wff.nasa.gov/topex/OscDrift.html, 1996.

Hayne, G. S., D. W. Hancock, and C. L. Purdy, TOPEX altimeter range stability estimates from calibration mode data, *TOPEX/POSEIDON Research News*, 3, pp. 18-22, 1994, (http://osb3.wff.nasa.gov/topex/docs/RangeStabUpdate.html).

Hendricks, J. R., R. R. Leben, G. H. Born, and C. J. Koblinsky, EOF Analysis of Global TOPEX/POSEIDON Data and Implications for Detection of Global Sea Level Rise, *J. Geophys. Res.*, 101(C6), 14131-14145, 1996.

Maul, G. A., and D. M. Martin, Sea level rise at Key West, Florida, 1846-1992: America's longest instrument record?, *Geophys. Res. Lett.*, 20(18), 1955-1958, 1993.

Menard, Y., Jeansou, and P. Vincent, Calibration of the T/P altimeters over Lampedusa, additional results over Harvest, *J. Geophys. Res.*, 99(C12), 24487-24504, 1994.

Minster, J.-F., C. Brossier, P. Rogel, Variations of the mean sea level from TOPEX/POSEIDON data, *J. Geophys. Res.*, 100(C12), 25153-25162, 1995.

Mitchum, G. T., Comparison of TOPEX Sea Surface Heights and Tide Gauge Sea Levels, *J. Geophys. Res.*, 99(C12), 24541-24554, 1994.

Mitchum, Gary T., Monitoring the stability of satellite altimeters with tide gauges, *J. Atmos. and Oceanic Tech.*, in press, 1997.

Morris, C. S., and S. Gill, Evaluation of the TOPEX/POSEIDON Altimeter System over the Great Lakes, *J. Geophys. Res.*, 99(C12), 24527-24540, 1994.

Murphy, C. M. and P. Moore, Calculation of TOPEX altimeter range bias drift using tide gauge augmented single satellite crossovers, *Adv. Space Res.*, in review, 1996.

Nerem, R. S., Global mean sea level variations from TOPEX/POSEIDON altimeter data, *Science*, 268, 708-710, 1995a.

Nerem, R. S., Measuring global mean sea level variations using TOPEX/POSEIDON altimeter data, *J. Geophys. Res.*, 100(C12), 25135-25152, 1995b.

Rapp, R. H., Y. Yi, and Y. M. Wang, Mean sea surface and geoid gradient comparisons with Topex altimeter data, *J. Geophys. Res.*, 99(C12), 24657-24668, 1994.

Reynolds, R. W., and T. S. Smith, Improved global sea surface temperature analysis, *J. Climate*, 7, pp. 929-948, 1994.

Wang, Y. M., and R. H. Rapp, Estimation of sea surface dynamic topography, ocean tides, and secular changes from Topex altimeter data, Dept. of Geodetic Sci. and Surv., The Ohio State Univ., Rep No. 430, 1994.

White, W. B., and C.-K Tai, Inferring interannual changes in global upper ocean heat storage from TOPEX altimetry, *J. Geophys. Res.*, 100, 24,943-24,954, 1995.

White, N. J., R. Coleman, J. A. Church, P. J. Morgan, and S. J. Walker, A southern hemisphere verification for the TOPEX/POSEIDON satellite altimeter mission, *J. Geophys. Res.*, 99(C12), 24505-24516, 1996.

Zanife, O., P. Escudier, and P. Vincent of CNES are credited with discovering the software error in June 1996.

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