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R. S. Nerem
University of Colorado at Boulder

G. T. Mitchum
University of South Florida, mitchum@usf.edu

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Estimates of vertical crustal motion derived from differences of TOPEX/POSEIDON and tide gauge sea level measurements

R. S. Nerem
Colorado Center for Astrodynamics Research, University of Colorado at Boulder, USA

G. T. Mitchum
College of Marine Science, University of South Florida, USA

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[1] We have computed estimates of the rate of vertical crustal motion from differences of sea level measurements made by the TOPEX/POSEIDON radar altimeter and a globally distributed network of 114 tide gauges. A rigorous error analysis was performed which suggests the accuracy of the estimated vertical rates is approximately 1–2 mm/year for roughly half of the tide gauges, which is sufficiently accurate to detect a variety of geophysical phenomena. While only a cursory analysis of the estimated crustal motion rates was performed, we observed many interesting phenomena including significant uplift at volcanic islands in the Pacific and uplift of 7–9 mm/year along the southwest coast of Alaska. The results reported here will be useful in a variety of geophysical studies, as well as for validation of similar estimates of vertical crustal motion provided by precise geodetic techniques such as SLR, DORIS, GPS, and VLBI. *INDEX TERMS:* 1294 Geodesy and Gravity: Instruments and techniques; 4294 Oceanography: General: Instruments and techniques; 4556 Oceanography: Physical: Sea level variations. **Citation:** Nerem, R. S., and G. T. Mitchum, Estimates of vertical crustal motion derived from differences of TOPEX/POSEIDON and tide gauge sea level measurements, *Geophys. Res. Lett.*, *29*(19), 1934, doi:10.1029/2002GL015037, 2002.

1. Introduction

[2] Vertical motion of the Earth's crust occurs due to a variety of phenomena including tectonic activity, glacial isostatic adjustment [*Milne et al.*, 2001], volcanic activity, and subsidence due to both natural and anthropogenic causes [*Bawden et al.*, 2001]. It also directly affects the measurement of relative sea level change made from tide gauges, thus vertical crustal motion is of great geophysical interest. Only recently have estimates of vertical crustal motion begun to emerge from the analysis of precise geodetic data, such as Satellite Laser Ranging (SLR), the Global Positioning System (GPS) [*Larson and van Dam*, 2000; *Milne et al.*, 2001; *Wahr et al.*, 2001], Very Long Baseline Interferometry (VLBI) and DORIS [*Soudarin et al.*, 1999], thus it is desirable to be able to corroborate these measurements using an independent measurement technique.

[3] Because vertical crustal motion directly affects sea level measurements made at tide gauges (which are attached to the crust), independent measurements of sea level could be used to isolate the crustal motion contained in the tide gauge data. The TOPEX/POSEIDON (T/P) radar altimeter satellite has been making independent measurements of sea level in a precise Earth-centered reference frame since its launch in late 1992 [*Fu et al.*, 1994]. These measurements have a point-to-point accuracy of 3–4 cm [*Cheney et al.*, 1994]. Differences between sea level measurements made by T/P and tide gauges have been used successfully to monitor the performance of the altimeter [*Chambers et al.*, 1998; *Mitchum*, 1997; *Mitchum*, 1994; *Mitchum*, 1998; *Mitchum*, 2000]. Independent assessments constrain the instrument drift to less than 1 mm/year [*Christensen et al.*, 1994; *Hayne et al.*, 1994; *Morris and Gill*, 1994]. Since the T/P instrument drift is quite small, we decided to turn the problem around and use the same measurements to estimate vertical crustal motion at each tide gauge location. A similar analysis was done by *Cazenave et al.* [1999], but the present analysis involves many more tide gauges, takes advantage of the longer time series available since that time, and provides a more rigorous error analysis.

2. Data Analysis

[4] First, we correct the T/P sea level measurements for instrument drift using the tide gauge calibration results of *Mitchum* [2000]. The net effect of this step is that the average vertical crustal motion at the 114 tide gauges will go into the altimeter drift estimate (which creates an error in the drift estimate which we one day hope to correct through geodetic monitoring of the tide gauges), and thus the vertical crustal motion rates we report here are relative to the ensemble mean, which is almost certainly much less than 1 mm/year for the well distributed set of gauges we have employed.

[5] The locations of the 114 tide gauges used in this study are shown in Figure 1. The orbit of T/P repeats every 10 days and has roughly a 300 km spacing between tracks at the equator [*Fu et al.*, 1994]. Thus, some care must be taken to match up the daily-average sea level measurements made at the tide gauges with the 10-day sea level measurements from T/P, since the tide gauges will not generally underlie the T/P groundtrack. This process is described in detail in *Mitchum* [2000]. Once we have a time series of the sea level differences, we simply determine the rate of vertical crustal

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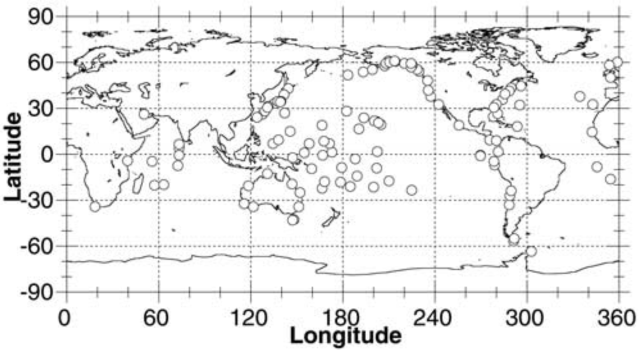

Figure 1. Locations of tide gauges used in this study.

motion from a least squares fit to these differences. The electronic supplement[1] shows the vertical crustal motion rates derived from the sea level differences. This table also shows the length of the time series available, up to the T/P series length of about 7.5 years, but usually shorter depending on the length of the tide gauge time series. Note that this is just the total record length spanned, and doesn't reflect possible gaps in the time series.

[6] It is important to pay careful attention to the reference frame when reporting estimates of vertical crustal motion [*Argus*, 1996]. For this study, the reference frame in which we are reporting the vertical rate estimates is essentially identical to the reference frame within which the T/P orbits are computed [*Nerem et al.*, 2000]. Currently, the T/P reference frame is not formally based on the International Terrestrial Reference Frame (ITRF), as ITRF92 was considered inadequate at the beginning of the mission (due principally to a lack of DORIS station positions). Currently, the SLR and DORIS station coordinates used for the precision orbit computations [*Tapley et al.*, 1994] are based on the CSR95L01/95D02 solution, which includes 3-D velocities for most sites. Geocenter motion, which is the motion of the center-of-mass of the Earth in this crust-fixed reference frame, is not currently modeled. CSR polar motion estimates derived from SLR tracking of Lageos are also employed. The station coordinates have been updated twice during the T/P mission, with a negligible impact on the orbit computations. The latest ITRF solution (ITRF96) is very close to the T/P adopted station coordinates, and future ITRF solutions can be considered for adoption by T/P and future missions.

3. Error Analysis

[7] Given that one eventual goal of these calculations is to provide a source of information about crustal motion that is independent of GPS or DORIS measurements, it is important to place realistic error estimates on the rates we report. At each tide gauge, the error variance of the vertical rate estimate is given by:

$$\sigma_{total}^2 = \sigma_{formal}^2 \times F_I + (0.4\mathrm{mm/yr})^2 \qquad (1)$$

where 0.4 mm/yr is the error in the T/P instrument calibration [*Mitchum*, 2000], σ_{formal} is the formal error of the rate estimate based only on the scatter of the fit residuals assuming all the points are independent, and F_I is an inflation factor to account for serial correlation in the fit residuals. σ_{formal} is computed as:

$$\sigma_{formal}^2 = 12 \times \sigma_{residuals}^2 \times \frac{\Delta t}{T_{record}^3} \qquad (2)$$

where $\sigma_{residuals}$ is the standard deviation of the residuals about the linear fit, Δt is the T/P orbit repeat period in years (~9.9159/365.25), and T_{record} is the record length in years.

[8] The inflation factor, F_I, was estimated by several methods. We computed the widely-used estimate based on assuming a first order Markov process (e.g., *Maul and Martin*, [1993]) both by using only the lag 1 autocorrelation values as well as by fitting the theoretical first order Markov function to the lagged autocorrelation sequence. We also estimated spectral slopes from the fit residuals and simulated error estimates via a Monte Carlo simulation, as suggested by *Mao et al.* [1999]. Finally, by analogy with the first order Markov process method, we also fit a Gaussian function to the lagged autocorrelation computed from the fit residuals and computed the appropriate variance inflation factor. This approach was motivated by the fact that the Gaussian function generally provided a much better approximation to the computed autocorrelation estimates. In fact, all of these estimates provide similar error variances, although all are significantly larger than assuming that the residuals are white; i.e., from assuming that $F_I = 1$. In the following we present results from the Gaussian fit approach, in which the inflation factor is given by:

$$F_I = 1 + \sqrt{\pi}\left(\frac{r_o}{\alpha}\right) \qquad (3)$$

where r_o and α are given from fitting the lag correlation sequence in the form:

$$r(\tau) = r_o e^{-(\alpha\tau)^2} \qquad (4)$$

and τ is the lag number.

[9] The electronic supplement shows the total error based on equation (1) using the Gaussian noise model. We consider this final error estimate to be the best 1 sigma error bar for the trends shown in the same table. Note that 60 of the 114 tide gauges have vertical rate errors less than 2 mm/year. The error is of course highly dependent on record length, and thus will improve as the record length from T/P (and soon its follow-on Jason-1) lengthens. Using the median values of $\sigma_{residuals}$ (30 mm) and the ratio r_o/α (1.1) that we observed in our dataset, the median error for our analysis approaches 1 mm/yr after about a decade.

[10] We also considered a few other factors that might influence the total error. For example, we nominally compare the tide gauge sea levels to 8 different T/P tracks, but sometimes these are not all available due to the land around the tide gauge. We therefore considered the error dependence on the number of tracks used. We also considered the distance to the closest of these tracks, as well as the average distance to all the tracks used. Generally, the larger these numbers are, the poorer sea level compares between T/P and the tide gauge, and the error estimate for the rate is

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[1] Supporting material is available via Web browser or via Anonymous FTP from ftp://ftp.agu.org, directory "append" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

correspondingly larger. Some unique aspects of each tide gauge are not reflected in the electronic supplement, such as when the tide gauge is located in an inland harbor isolated from the T/P tracks (e.g., Anchorage), resulting in much larger (and possibly underestimated) errors.

[11] Our crustal motion rates sometimes disagree at greater than the 2σ level with the rates at 8 common sites reported by *Cazenave et al.* [1999]. We believe this is because they reported only the 8 largest rates for the 53 gauges they analyzed, and thus statistically it would not be unexpected that some of these would be 2–3 standard deviations from the true rate. In addition, our analysis includes several years more data, perhaps allowing us to better average through the ENSO event at the end of the *Cazenave et al.* time series.

4. Discussion of Results

[12] It should first be noted that the vertical motion rates given in the electronic supplement could have several possible sources. If careful leveling is not done on an regular basis between the tide gauge and the tide gauge benchmarks on land, then the rate might reflect a combination of crustal motion and motion of the pier to which the tide gauge is attached. While we know that the benchmark ties are well maintained for many of the gauges, we have little information on a significant fraction of the gauges. In addition, if the long-term behavior of the ocean is different between the tide gauge location (usually a harbor) and the open ocean locations of the T/P data, this will introduce an error into our estimates. We believe that these instances are rare, but each tide gauge must be evaluated on an individual basis.

[13] Most of the tide gauges in southwest Alaska show significant uplift (Kodiak Island 8.7 ± 1.3 mm/yr, Adak Island 7.1 ± 1.9 mm/yr, Dutch Harbor 6.5 ± 1.7 mm/yr, Yakutat 8.0 ± 2.0 mm/yr, Seldovia 10.3 ± 2.4 mm/yr) which is consistent with geophysical studies of the region [*Cohen and Freymueller*, 2001; *Freymueller et al.*, 2000; *Sauber et al.*, 1997]. This uplift is not present in southeast Alaska (Ketchican −1.6 ± 2.7 mm/yr, Sitka −0.6 ± 2.6 mm/yr).

[14] Two tide gauges in northern Japan show significant subsidence (Kushiro −5.1 ± 1.2 mm/yr, Ofunato −4.6 ± 2.6 mm/yr), which could represent a post-seismic response to the 1993 Kushiro-Oki earthquake [*Takeo et al.*, 1993]. In addition, one of the Japanese islands, Miyakejima, which has been undergoing recent volcanic activity [*Ukawa et al.*, 2000], shows significant uplift (34.1 ± 8.9 mm/yr). Several other stations show statistically significant uplift (Manzanil 7.5 ± 1.8 mm/yr, Crescent 5.6 ± 2.3 mm/yr, Kapingam 5.4 ± 1.7 mm/yr, Esperanc 4.5 ± 1.5 mm/yr, Baltra 4.2 ± 1.3 mm/yr, Saipan 4.2 ± 2.0 mm/yr, Mombasa 2.6 ± 1.7 mm/yr, Noumea 2.5 ± 1.5 mm/yr) or subsidence (Fremantle −8.5 ± 3.0 mm/yr, Nuku'alo −7.9 ± 2.5 mm/yr, Gan −7.0 ± 1.2 mm/yr, Darwin −6.2 ± 1.2 mm/yr, French Frigate −5.7 ± 1.2 mm/yr, Ascension −3.7 ± 1.2 mm/yr, Charleston −3.2 ± 1.5 mm/yr, Diego Garcia −3.2 ± 1.9, Port Vil −2.9 ± 1.6, Mera −2.8 ± 1.7, Bundaber −2.4 ± 1.5, Christmas Island −2.3 ± 1.0, Lerwick −1.9 ± 1.1, and Papeete −1.8 ± 1.1) of an origin we did not investigate, although many of these sites are affected by fluid withdrawl (water and/or hydrocarbons, e.g., [*Bawden et al.*, 2001]) and volcanic activity.

[15] Computing vertical crustal motion estimates naturally leads one to try to compare these estimates to those from satellite geodetic measurements, such as GPS and DORIS. We obtained several different solutions from various research groups. Figure 2 is representative of the comparisons that we obtained to a set of DORIS results [*Soudarin et al.*, 1999] and a set of GPS results [*Heflin et al.*, 1992; *Argus and Heflin*, 1995; *Zumberge et al.*, 1997]. While some correlation is observed, the overall agreement is not what one would hope. We observed the same level of agreement between the different satellite solutions, even between different GPS solutions computed by different research groups. Our conclusion, which is supported by the relative paucity of vertical rate estimates in the literature, is that our ability to determine the rate of vertical crustal motion from any technique is still being developed, and certainly some improvements are needed. Thus, one of the purposes of this paper is to provide a set of vertical crustal motion rates whose errors are largely independent of rates determined from the traditional satellite geodesy techniques.

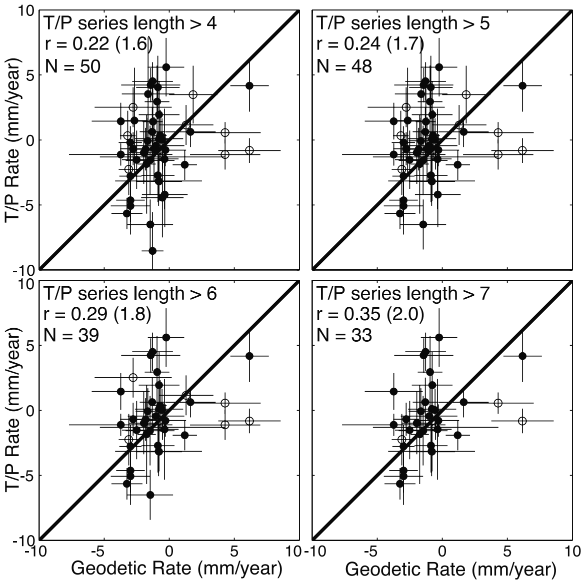

Figure 2. Comparison of the vertical rate estimates from this investigation with rate estimates made at nearby GPS (solid circles) and DORIS (open circles) geodetic sites. Rate differences greater than 10 mm/yr have been excluded from this comparison.

[16] We also compared our derived vertical crustal motion estimates to semi-independent estimates we derived from the historical tide gauge data alone. This "internal estimate" was constructed by taking the negative of the long-term rate (over many decades) of sea level rise observed at each tide gauge and adding a "best estimate" of global mean sea level rise over the same time period (1.8 mm/year, *Douglas* [1991]) as discussed by *Mitchum* [2000]. For example, suppose a given tide gauge has observed a rate of sea level rise of 7 mm/year over the last 50 years, then the "internal estimate" of vertical crustal motion would be -5.2 mm/year. Figure 3 displays a comparison of the T/P-tide gauge vertical crustal motion estimates and the "internal estimates" for tide gauges where errors from both estimates were less than 3 mm/year. A linear least squares fit to these estimates, considering errors in both variables, resulted in a slope of 0.97 ± 0.13 and an intercept of −0.41 ± 0.25. The intercept estimate is only slightly different

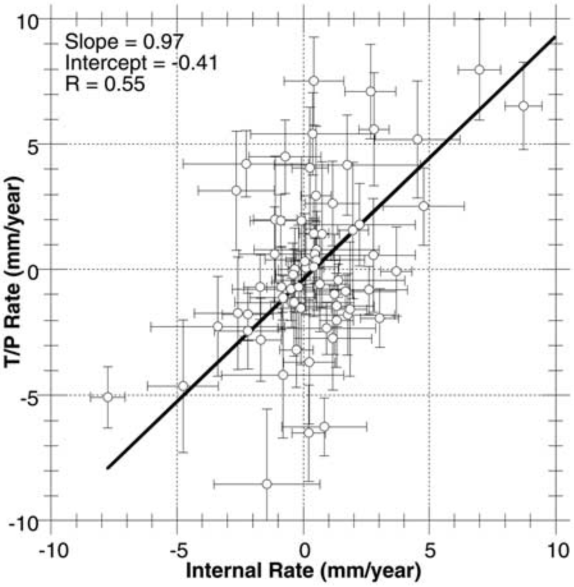

Figure 3. Comparison of the vertical rate estimates from this investigation with rate estimates determined by substracting 1.8 mm/year [*Douglas*, 1991] from the negative of the long-term sea level change rate observed over the entire tide gauge record. Points were included only if both errors were less than 3 mm/year.

from zero in a statistical sense, and probably reflects an error in the 1.8 mm/year global sea level rate used (a rate that was smaller by 0.4 mm/year would eliminate the intercept). In general, the comparison shown in Figure 3 is quite good, though the estimates are not quite independent, as both employ tide gauge data during the T/P time frame.

5. Conclusions

[17] We have shown that vertical crustal motion rates can be derived from T/P and tide gauge sea level differences with accuracies of $\sim$1 mm/year for open ocean/island sites with continuous records covering the entire T/P mission. In many cases, the observed rates can be related to known geophysical phenomena. Comparisons of these results to satellite geodetic results are inconclusive due to the immaturity of the geodetic solutions for vertical positions, as well as errors in our results. As such, the results reported here should be regarded as validation targets for future satellite geodetic solutions, although each tide gauge needs to be evaluated on a case-by-case basis to determine if its motion reflects true crustal motion, or represents local motion of the pier, tide gauge benchmark, etc.

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G. T. Mitchum, College of Marine Science, University of South Florida, 140 Seventh Ave. South, St. Petersburg, FL 33701. (mitchum@seas.marine.usf.edu)

R. S. Nerem, Colorado Center for Astrodynamics Research, University of Colorado, UCB431, Boulder, CO 80309-0431. (nerem@colorado.edu)