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D. P. Chambers
University of Texas at Austin, donc@usf.edu

J. C. Ries

C. K. Shum

B. D. Tapley

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On the use of tide gauges to determine altimeter drift

D. P. Chambers, J. C. Ries, C. K. Shum[1], and B. D. Tapley

Center for Space Research, University of Texas at Austin

Abstract. TOPEX measurements of sea level variability have been compared to tide gauge measurements from 40 sites and to dynamic topography measurements computed from temperatures recorded at 23 Tropical Ocean-Global Atmosphere (TOGA)-Tropical Atmosphere-Ocean (TAO) buoys in the eastern Pacific and mean temperature-salinity profiles. Buoy data in the western Pacific were not used because of large long-term slopes in the data that appear to be due to interannual salinity variations. The relative drift between TOPEX and the two different in situ sets of data agree within 1 mm yr^{-1}, with a weighted average of -2.6 mm yr^{-1} and an estimated uncertainty of 1.5 mm yr^{-1}, if values from an internal calibration of the TOPEX altimeter are applied. The consistency of the two relative drifts suggests that the slope is due at least in part to a drift in the TOPEX measurement. A substantial portion of this drift may be due to a drift in the TOPEX microwave radiometer (TMR), since comparisons with three independent external measurements indicate a drift in sea level due to the TMR measurement of about -2 mm yr^{-1}.

1. Introduction

One of the most troubling aspects of using satellite altimeters to monitor global sea level change is the problem of the long-term drift in the altimeter measurement [*Born et al.*, 1986; *Tapley et al.*, 1992; *Wagner and Cheney*, 1992; *Nerem*, 1995; *Nerem et al.*, 1997]. Several methods have been used to monitor and measure drifts in the altimeter measurement. For the TOPEX/POSEIDON (T/P) mission, an on board circuit was built into the TOPEX altimeter to measure changes in the range caused by deterioration of the altimeter circuitry [*Hayne et al.*, 1994]. The results of this internal calibration suggest a drift in the sea level measurement due to the altimeter circuitry that is not linear (Figure 1). However, the calibration mode was originally required to measure drifts of the order of a centimeter over a 10-day repeat cycle [*Hayne et al.*, 1994], which means that the drift values that are reported are well within the uncertainty of the calibration design. The stability of the internal calibration suggests that it performs considerably better than 1 cm per cycle, but how much better is difficult to assess without additional calibration information.

Another method used to determine drift in the sea level measurement is the comparison of the measurement made by the altimeter (including all the media corrections) with the sea level measured by a precisely located and calibrated tide gauge near the satellite ground track. This was done for TOPEX/POSEIDON at two sites: Harvest platform off the coast of California [*Christensen et al.*, 1994] and Lampedusa in the Mediterranean Sea [*Ménard et al.*, 1994]. The results of the calibration over the first year of the TOPEX/POSEIDON mission show agreement at the 3-cm rms level [*Christensen et al.*, 1994; *Ménard et al.*, 1994]. A more recent analysis at the Harvest platform using data through the third year of the mission shows agreement at the 2.3-cm rms level [*Haines et al.*, 1996].

While these results are encouraging as to the overall accuracy of the TOPEX measurement, the relatively large scatter suggests that drifts of the order of a few mm yr^{-1} cannot realistically be detected by this approach using only a few years of data. Over a very long time span, though, the drift will be more separable. Considering that the global sea level change estimated from tide gauges is around 1 - 2 mm yr^{-1} [*Douglas*, 1991], an unknown drift at the same level in the altimeter measurement could lead to erroneous inferences of global sea level change in the short term.

More recently, *Mitchum* [1998] has suggested using a large number of island and coastal tide gauges to compare with the altimeter measurements in order to separate the drift at shorter time scales. Although these gauges are generally not as well calibrated as the Harvest and Lampedusa gauges, averaging the larger number of satellite/tide gauge differences should reduce random errors that tend to be large when comparisons are made at only a single site. By averaging comparisons over 53 sites, *Mitchum* [1998] has reduced the standard deviation of the signal to < 1 cm. At this level, drifts of the order of several mm yr^{-1} in the satellite altimeter should be detectable.

In fact, *Mitchum* [1998] has demonstrated that a large, quadratic drift in the TOPEX measurement due to an improperly applied oscillator correction is seen in the averaged difference time series. Before the error was discovered in July 1996 (D. Hancock and G. Hayne, personal communication, 1996), the sea level measured by TOPEX was rising at a rate about 5 - 7 mm yr^{-1} higher than that observed by the tide gauges. This was nearly the size of the error in the TOPEX measurement due to the improperly applied oscillator correction.

Although *Mitchum* [1998] has demonstrated that the technique of averaging a large number of satellite/tide gauge differences can detect drifts of the order of 5 - 10 mm yr^{-1}, there is some question as to whether a 1 - 2 mm yr^{-1} drift is detectable. Because there is little knowledge of vertical motion at the tide gauges, part of the relative drift could be due to subsidence or uplift at these mostly volcanic islands. *Mitchum* [1998] has indicated that the post glacial rebound at the sites is much less than 1 mm yr^{-1} and averages to near zero. However, measurements of the vertical motion with Global Positioning System (GPS) data by the International GPS Service for Geodynamics show large vertical motions for at least three of the islands: Guam (5 mm yr^{-1}), Hawaii (-6 mm yr^{-1}), and French Polynesia (5 mm yr^{-1}). There are no measurements at the other islands, so it is unknown whether the average vertical motion over the island gauges will be small or whether it might be significant. Therefore, one cannot say for certain that the result reported by *Mitchum* [1998] is due wholly or in part to a drift in the TOPEX altimeter, since we do not know what the averaged vertical motion of the tide gauges is.

In this paper, we will try to verify that there is a drift in the TOPEX measurement by comparing the altimeter data to both tide gauge data and another set of data, dynamic topography

[1]Now at Department of Geodetic Science and Surveying, The Ohio State University, Columbus.

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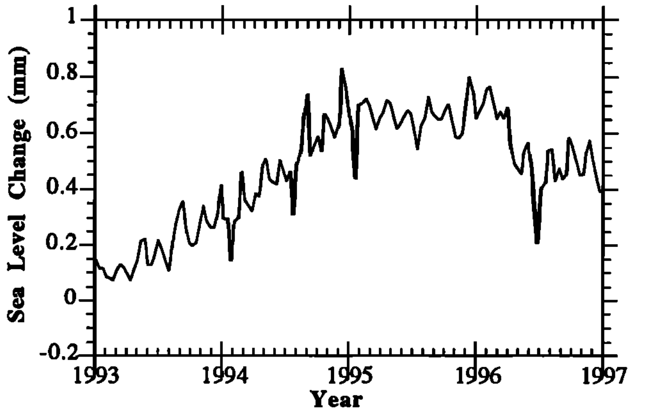

Figure 1. Range corrections from the Wallops internal calibration in terms of the effect on sea level measurement.

calculated from temperature measurements made at moored buoys. Since the buoy data will not be affected by tectonic motion as the island tide gauges are, a similar relative drift with TOPEX will be stronger evidence of a drift in the altimetric measurement. Although the Tropical Atmosphere-Ocean (TAO) buoy measurements are not ideal for this type of calibration, they represent the only comparable large set of in situ measurements that can be used to verify the drift suggested by the tide gauge comparisons.

2. Data Processing and Intercomparison

For this study, we have used data over the time period from January 1993 through December 1996. The TOPEX altimeter data (repeat cycles 10 - 161) are from the first release geophysical data records (GDRs) [*Callahan*, 1993], with several changes. Data from the separate POSEIDON altimeter are not used. The GDR orbits have been replaced with those computed with the Joint Gravity Model (JGM-3) at the University of Texas Center for Space Research (UT/CSR), the ocean tide model has been replaced with the UT/CSR 3.0 model [*Eanes and Bettadapur*, 1995], and the pole tide has been corrected. The data have been corrected to fix the error caused by the misapplied oscillator correction before cycle 132, using a time series provided by D. Hancock and G. Hayne at the Wallops Flight Facility. We have not applied the drift detected by the internal calibration mode to the data at this time, but we will discuss the implications of its use in the next section. The inverted barometer correction has not been applied to the altimeter data, because the tide gauge data are not pressure corrected, pressure variations in the tropics are small, and the inverted barometer model suggested in the GDR handbook is considered to be unreliable in the tropics [*Fu and Pihos*, 1994].

The tide gauge data are obtained as daily averages from the World Ocean Circulation Experiment (WOCE) Fast Delivery Sea Level Center at the University of Hawaii [*Mitchum*, 1994]. Because island stations are more typical of deep ocean conditions (which the satellite measures), this analysis has been limited to the 46 island gauges in the Atlantic, Pacific, and Indian Oceans, which were observed throughout the T/P mission. The sites at Socorro and San Felix have consistently been anomalous [*Mitchum*, 1994], while the listing for Chatham in the South Pacific appears to have an incorrect latitude and longitude. Pago Pago has an anomalous 5-cm bias for several months in the middle of the record. Because of these problems, we have eliminated these 4 sites, leaving 42 possible sites for comparisons (Figure 2). The tide gauges are biased toward the Pacific Ocean (34 sites), with only 7 gauges in the Indian Ocean and 1 site in the Atlantic. Of the 42 sites, 41 were observed throughout the first 4 years of the TOPEX/POSEIDON mission; one (Nuku Hiva) was observed for only 1.75 years, so it was not used in the averaged comparisons described later.

Daily averaged temperature measurements at the surface of the ocean and at fixed depths were obtained from tethered buoys that are part of the Tropical Ocean and Global Atmosphere-Tropical Atmosphere-Ocean (TOGA-TAO) array. The data were obtained from the archive at the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory [*McPhaden*, 1993]. There are currently 75 buoys in the data set. Five were immediately removed because they moved more than 100 km during 1992 - 1997, most likely because of a broken tether. Since we want the TAO dynamic topography variations to match TOPEX sea level variations as closely as possible, we computed the dynamic topography at each site to the lowest level available. This is 300 m at most buoys but is 500 m at about a quarter of the sites. If there were too little data for a site at 500 m, the 300-m level was used instead.

Since the TAO buoys do not collect salinity measurements, we used monthly temperature-salinity (*T-S*) relationships for each site derived from the *World Ocean Atlas 1994* database [*Levitus et al.*, 1994] to compute salinity, then we used the recorded temperatures and the international equation of state [*United Nations Educational, Scientific, and Cultural Organization*, 1981] to compute density at each level before integrating from the lowest level to the surface to compute dynamic topography. The estimated accuracy of dynamic topography computed in this manner is about 3 cm in the western Pacific and 2 cm in the eastern Pacific [*Busalacchi et al.*, 1994].

The use of climatological salinity values can lead to potentially large differences between the TOPEX and TAO measurements, particularly in terms of relative drift. In the western Pacific, salinity varies strongly with the El Niño cycle [*Delcroix and Henin*, 1991]. Salinity and hence water density increase from El Niño to La Niña, the portion of the cycle from 1993 to 1996, which means that the dynamic topography computed with mean salinity will be erroneously high. A recent investigation [D. P. Chambers et al., manuscript in preparation, 1998] indicates that the error in sea level rate in this regioncan be as large as 2 cm yr^{-1}. However, the salinity variations are only significant in the region west of 200°E. Thus, for the final analysis of relative drift, only TAO data west of 200°E will be used. This will be discussed more in the next section.

After computing the dynamic topography, 20 TAO sites were eliminated because they had numerous extended data outages. Ten of these had < 1 complete year of observations. Two more sites were removed because of a large change in the dynamic topography after a data outage. Six additional sites were removed because there were fewer than 20 TOPEX observations near them for each repeat cycle. This left 42 sites for our analysis (Figure 2).

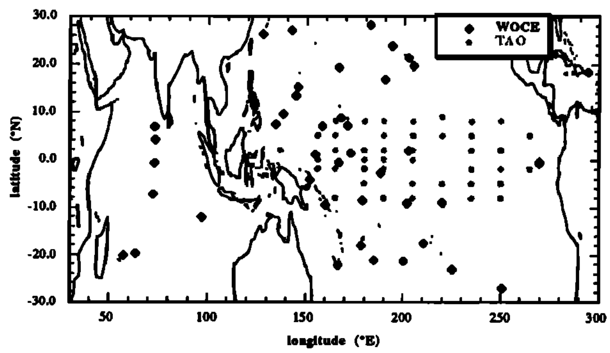

Figure 2. Locations of World Ocean Circulation Experiment (WOCE) tide gauges and Tropical Atmosphere-Ocean (TAO) buoys used in this study.

Because each of these data have different references and we are only interested in the drift, we use anomalies, or deviations about a mean, in our analysis. For the WOCE and TAO data, this is a simple calculation. After computing a long-term average of the data at each tide gauge or buoy, we remove the average from the data to compute an anomaly. The computation of the anomaly for the TOPEX measurements is slightly more difficult because of the fact that the altimeter measurements are not made at a single point like a tide gauge but are scattered over a small area due to cross-track drift and the 1-s sampling rate. This can cause significant errors due to sampling of steep geoid gradients [*Brenner et al.*, 1990].

We have minimized this error by computing TOPEX sea level anomalies relative to a high-resolution mean sea surface (MSS) [*Chambers et al.*, 1998]. The MSS has a 1-s along-track resolution, and each 1-s bin is a plane for which the parameters (along-track gradient, cross-track gradient, and mean height at the center) have been estimated from all the available data after removing any linear trend as well as annual and semi annual variability. Removing these periodic signals is necessary because the altimeter samples the bin in time as well as space, and we have found that the periodic signals can be aliased into the gradients if not accounted for. All the data from any bin are edited if the along-track gradient of the MSS exceeds ± 60 μrad (an 18-cm change in MSS over 3 km), if less than 2 years of data are used to estimate the plane parameters, or if the water has a depth of < 100 m. This still leaves from 50 to 100 TOPEX observations around each tide gauge or buoy per repeat cycle.

Once anomalies of each data type have been computed, the data are differenced as follows. First, all the TOPEX data in an area 2° north-south and 4° east-west centered on a tide gauge or buoy are averaged over each T/P repeat cycle (10 days) to reduce the random errors in the TOPEX data by averaging measurements from at least one, but usually two, ascending and descending passes. The tide gauge and buoy daily data are also averaged over the T/P repeat cycle to average out high-frequency variations that are not sampled by the altimeter. Table 1 lists the rms of the differences and the correlations between the TOPEX anomalies and in situ data at each site. The tide gauge differences have a mean rms of 3.5 cm and a correlation of 0.87, comparable to the values observed by *Mitchum* [1994]. The TAO differences have a similar mean rms of 3.7 cm and a slightly lower correlation of 0.8. This is comparable to the results of *Menkes et al.* [1995], although they indicate slightly higher rms values in the western Pacific than we observe. Since we are interested in long-period signals, we have also low-pass filtered the time series with a 90-day (nine repeat cycle) boxcar filter. As Table 1 indicates, this reduces the rms of the comparisons by 1 cm and also increases the correlations.

To examine the relative drift between TOPEX and the in situ data, we will difference the anomalies and average them over the domain of the tide gauge or TAO networks for each repeat cycle,

$$\Delta_j = \frac{\sum_{i=1}^{n}\left(\Delta\eta_{\mathrm{TOPEX}} - \Delta\eta_{\mathrm{situ}}\right)_{i,j}}{n} \tag{1}$$

where i is the particular in situ site, j is the particular repeat cycle, n is the total number of sites where the difference exists, $\Delta\eta_{\mathrm{TOPEX}}$ is the sea level anomaly from the TOPEX data, and $\Delta\eta_{\mathrm{situ}}$ is the sea level anomaly from the in situ data. After using (1) for every repeat cycle, one has a time series of differences, Δ_j, which represent the average difference between the TOPEX measurements and the WOCE tide gauge or TAO measurements. Since identical signals will difference out, the slope of the time series should represent drift in the TOPEX sea level measurement if there is no average drift in the in situ data.

We also compute a similar time series and slope at each site. These individual site slopes will be used to determine if any site

Table 1. RMS and Correlations of TOPEX/Tide Gauge and TOPEX/TAO Comparisons

	10-day		90-day	
	RMS	ρ	RMS	ρ
Tide Gauge				
Pohnpei	2.83	0.92	1.57	0.97
Betio	2.19	0.91	1.40	0.93
Baltra	3.29	0.79	1.99	0.91
Nauru	3.47	0.81	2.54	0.82
Majuro	2.00	0.94	0.87	0.97
Malakal	2.93	0.93	1.62	0.96
Yap	2.65	0.94	1.11	0.97
Honiara	3.51	0.96	2.06	0.98
Rabaul	4.30	0.91	3.16	0.96
Christmas	2.57	0.89	1.32	0.95
Kanton	1.93	0.93	0.97	0.97
Fr. Frigate Shoals	4.77	0.82	2.74	0.91
Papeete	2.70	0.63	1.30	0.74
Rikitea	4.08	0.75	3.02	0.82
Suva	3.72	0.85	2.70	0.89
Noumea	4.38	0.67	2.51	0.77
Easter Island	3.50	0.79	1.77	0.90
Rarotonga	4.90	0.74	2.85	0.83
Penhryn	2.09	0.92	0.85	0.98
Funafuti	2.21	0.94	1.01	0.98
Saipan	3.30	0.91	2.31	0.94
Kapingamarangi	3.82	0.82	2.39	0.88
Santa Cruz	3.02	0.82	1.74	0.93
Nuku Hiva	1.69	0.79	0.75	0.83
Nuku'Alofa	4.16	0.78	1.62	0.92
Chichijima	6.32	0.86	2.64	0.96
Midway	5.17	0.63	3.01	0.74
Wake Island	5.01	0.79	2.10	0.92
Johnston	5.27	0.79	2.20	0.91
Guam	3.59	0.93	2.42	0.96
Kwajal	2.37	0.91	1.66	0.94
Honolulu	4.42	0.71	2.23	0.86
Hilo	4.10	0.70	2.12	0.83
Port Louis	4.86	0.84	2.61	0.92
Diego Garcia	2.42	0.94	1.01	0.98
Rodrigues	3.08	0.94	1.27	0.98
Hulhule	2.33	0.89	1.26	0.94
Gan	2.78	0.82	1.70	0.90
Hanimaadhoo	3.57	0.91	2.71	0.93
Cocos Island	4.97	0.87	3.61	0.90
San Juan	2.66	0.90	1.29	0.96
Naha	4.58	0.90	2.41	0.95
Mean	3.50	0.87	1.96	0.91
TAO Buoy				
0°N 155°W	2.52	0.92	1.34	0.96
0°N 156°E	6.76	0.74	5.74	0.80
0°N 170°W	3.02	0.89	1.47	0.95
0°N 180°W	3.99	0.74	2.74	0.79
2°N 110°W	2.21	0.90	1.06	0.96
2°N 125°W	2.29	0.88	1.58	0.90
2°N 137°E	4.87	0.86	4.58	0.88
2°N 155°W	2.86	0.89	1.74	0.93
2°N 165°E	4.27	0.75	3.54	0.75
2°N 170°W	3.10	0.83	2.56	0.86
2°N 180°W	3.77	0.69	2.58	0.78
2°S 110°W	2.25	0.90	0.89	0.97
2°S 125°W	2.57	0.91	1.55	0.96
2°S 156°E	5.46	0.88	5.62	0.86
2°S 165°E	5.44	0.72	4.60	0.81
2°S 170°W	3.74	0.74	2.47	0.83
2°S 180°W	3.46	0.73	2.62	0.69
2°S 95°W	2.48	0.86	1.73	0.90
5°N 125°W	4.47	0.84	1.78	0.95
5°N 140°W	4.59	0.85	2.63	0.92
5°N 155°W	3.63	0.91	2.63	0.93
5°N 156°E	3.55	0.91	2.07	0.95

Table 1. (continued)

	10-day RMS	10-day ρ	90-day RMS	90-day ρ
	TAO Buoy (continued)			
5°N 165°E	3.83	0.90	2.25	0.96
5°N 170°W	3.82	0.89	2.48	0.93
5°N 95°W	2.89	0.72	1.57	0.81
5°S 110°W	3.20	0.70	1.80	0.85
5°S 125°W	3.38	0.63	1.49	0.84
5°S 140°W	4.12	0.61	1.76	0.76
5°S 155°W	2.92	0.80	1.92	0.86
5°S 180°W	4.26	0.72	3.72	0.65
8°N 110°W	3.38	0.89	2.05	0.92
8°N 125°W	3.95	0.88	3.04	0.87
8°N 155°W	3.17	0.91	2.32	0.91
8°N 165°E	3.59	0.79	1.99	0.88
8°N 170°W	3.28	0.76	1.84	0.83
8°N 180°W	3.46	0.78	3.28	0.64
8°S 110°W	3.30	0.64	2.08	0.78
8°S 125°W	3.08	0.64	1.83	0.78
8°S 155°W	3.10	0.67	2.47	0.73
8°S 165°E	5.03	0.90	3.52	0.94
8°S 170°W	4.59	0.67	3.47	0.69
9°N 140°W	4.01	0.80	3.15	0.78
Mean	3.70	0.80	2.50	0.85

RMS values are given in centimeters; correlations are given by ρ.

has an anomalously large drift and to see if the relative slopes between TOPEX and the tide gauges or TOPEX and the TAO buoys are similar in similar regions. Differences could indicate a problem in either a tide gauge or buoy. In the following discussion, the time series will be referred to as WOCE (TOPEX minus WOCE) or TAO (TOPEX minus TAO).

2.1 Long-Term Relative Drift

We first examine the average WOCE time series (Figure 3) to see how well our estimate of relative drift compares with that of *Mitchum* [1998]. The time series has a linear slope of -1.2 ± 0.7 mm yr^{-1}, suggesting a drift between the two data. The error is determined from the covariance of the least squares estimate of the best fit curve (a bias and slope plus annual and semi annual sinusoids), where the data have been weighted by the standard deviation of the time series, 8 mm. *Mitchum* [1998] reports a value of -0.4 mm yr^{-1}; we note, however, that he used only data from repeat cycles 6 to 129. Using the same cycles, we find a similar slope (-0.6 mm yr^{-1}).

We now look at the TAO data to see if there is a similar relative drift with TOPEX. Before looking at the average time series, though, we will examine the relative drifts at individual buoys and tide gauges (Figure 4), which highlights the error introduced into the TAO dynamic topography when real salinity measurements are not used. The relative drifts at the tide gauges all lie between ± 15 mm yr^{-1}, except for one tide gauge (Rabaul), where the relative drift is -23 mm yr^{-1}. The standard deviation of the relative drifts at the tide gauges is 5.5 mm yr^{-1}. There is a dramatic difference in the relative drifts at the TAO buoys in the western Pacific. In the east, the relative drifts have a similar distribution as those with the tide gauges. The drifts get increasingly larger as the longitude increases to the west for the TAO buoys, with values as large as -40 mm yr^{-1}. The standard deviation of the relative drifts at the TAO buoys is nearly twice that of the tide gauges, about 11 mm yr^{-1}. This increase in the relative drift is due to the climatological salinity values in the

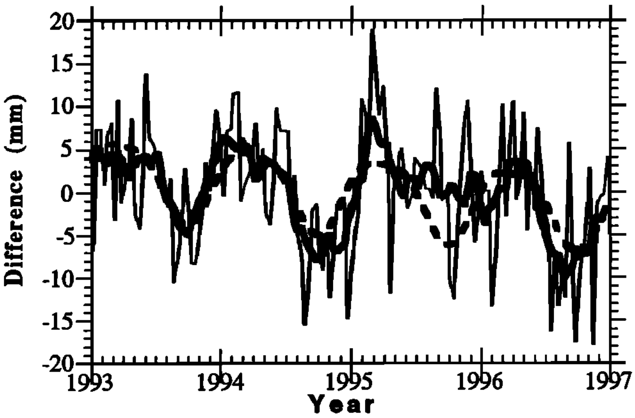

Figure 3. Time series of TOPEX minus WOCE tide gauge differences, averaged over 40 sites. The thin line is 10-day averaged differences, the thick solid line is 90-day smoothed differences, and the thick dashed line is the best fit bias, slope, and annual and semi annual sinusoids.

TAO data; since TOPEX measures sea level directly, it is sensitive to the interannual salinity fluctuations while the TAO data are not.

Because the long-term salinity variation is only significant in the western Pacific, we eliminated sites in that region from the averages computed with (1). This removed approximately half the available buoys. The standard deviation in relative drift of the remaining 23 sites is 5 mm yr^{-1}, about the size of the value from the tide gauge comparisons. The slope of the TAO time series averaged over these 23 sites (Figure 5) is -1.9 ± 1.0 mm yr^{-1}, which is the same sign as the slope of the WOCE time series, and agrees within the estimated error. Because of the more limited sample of the TAO data, we hesitate to put too much weight on the value of the drift estimated from that data set. Instead, an average drift is computed from the two estimates, weighting each estimate by the number of sites which went into the estimate. The result is -1.4 mm yr^{-1}.

The level of uncertainty in the analysis is harder to determine. The error based on the covariance of the slope estimate is ± 1.0 mm yr^{-1} (using the larger error from the TAO time series). However, we do not know the level of tectonic motion at the tide gauges or errors in the TAO dynamic topography due to long-term salinity variations. *Mitchum* [1998] speculates that the average vertical motion at the tide gauges is < ± 1 mm yr^{-1}. Our

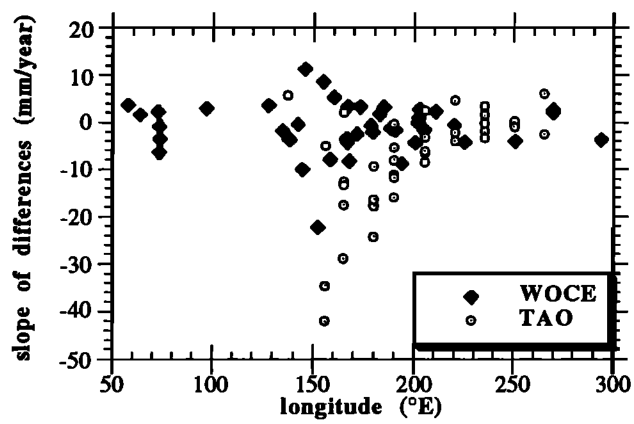

Figure 4. Slope of TOPEX minus WOCE tide gauge and TOPEX minus TAO differences at individual sites as a function of longitude.

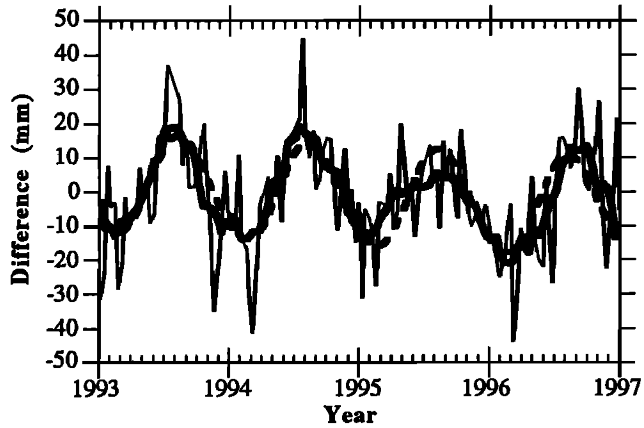

Figure 5. Time series of TOPEX minus TAO differences, averaged over 23 sites in the eastern Pacific. The thin line is 10-day averaged differences, the thick solid line is 90-day smoothed differences, and the thick dashed line is the best fit bias, slope, and annual and semi annual sinusoids.

results tend to support this assertion, since the difference in the slopes relative to the WOCE data and the TAO data disagree at this level. Another factor which needs to be considered is that although the two time series have similar long-term rates, there is significant variability at shorter periods (Figure 6), and the variations are quite different.

It is unclear what the source of these signals are. What is important to this discussion, though, is how these variations may affect the estimate of the long-term drift. The largest signal is at an annual frequency, although there are smaller signals at other frequencies. Several tests were conducted to estimate these other frequencies simultaneously with the drift; the resulting change in the estimate was < 0.2 mm yr^{-1} if the annual frequency was always estimated simultaneously with the linear slope. Thus, while these annual and intra-annual variations in the differences are interesting and are the subject of current investigations, they do not appear to adversely affect the estimate of the long-term relative drift if at least an annual sinusoid is estimated simultaneously. Using the root-sum-square of these errors, we believe the mean drift for TOPEX sea level is about -1.4 mm yr^{-1}, with an error of ± 1.5 mm yr^{-1}, if the TOPEX data are not corrected with the values from the internal calibration.

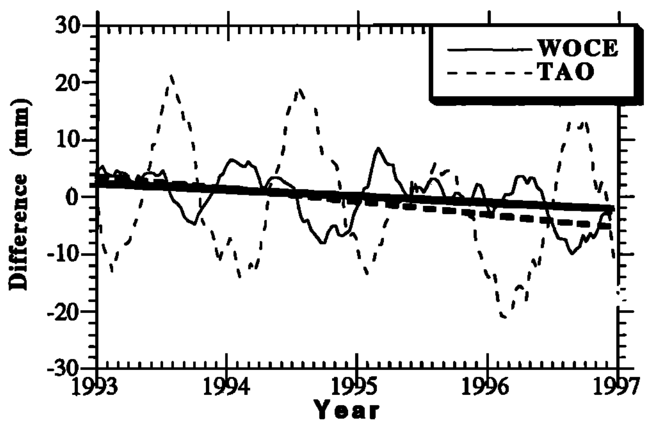

Figure 6. Time series of TOPEX minus WOCE tide gauge differences (solid curve) and TOPEX minus TAO differences (dashed curve). The thick lines are the linear portion of the best fit bias, slope, annual and semi annual sinusoids.

2.2 Possible Sources of Drift

The drift in the altimeter range measured by the internal calibration causes a sea level drift which is in the opposite direction of the drift observed between TOPEX and the in situ measurements. Rather than explaining the drift, then, the internal calibration suggests an even larger drift, since applying the calibration values to the TOPEX data will cause drifts relative to the in situ measurements to increase by -1.2 mm yr^{-1}, to -2.4 mm yr^{-1} for the WOCE time series and -3.1 mm $yr^{-1}$for the TAO time series. This means that the weighted mean drift is about -2.6 mm yr^{-1} if the internal calibration data are applied, as has been suggested by the TOPEX/POSEIDON Science Working Team [*Benada*, 1997].

Since the drift in the altimeter range measurements appears to not be the source of the drift in the sea level measurement, then the drift must lie in one or more of the corrections to the altimeter range which remove errors due to propagation through the atmosphere or scattering at the ocean surface. The correction for the dry troposphere comes from a model, but comparisons against real measurements around the globe show no apparent drift [*Kruizinga*, 1997]. A comparison between the ionosphere correction derived from the dual frequency altimeter and that determined from the Doppler orbitography and radiopositioning integrated by satellite (DORIS) tracking system also shows no relative drift (V. Zlotnicki, personal communication, 1997). We cannot compare the sea-state bias to any external measurement, since it is a property of the radar altimeter only. However, the long-term relative drift between the sea-state bias correction on the original GDRs and that which is included on the re released Merged GDRs [*Benada*, 1997] is only 0.3 ± 0.1 mm yr^{1}. Assuming the new sea-state bias model is more correct, this suggests that any long-term error in the GDR sea-state bias is much smaller than what we observe.

The final major media correction is the wet troposphere correction, measured by the TOPEX microwave radiometer (TMR). Suspicion first arose that there might be a drift in the TMR when it was observed that the brightness temperatures had a long-term drift (V. Zlotnicki, personal communication, 1996). Recently, the TMR path delay has been compared to several other direct measurements of path delay, including an upward looking water vapor radiometer at Harvest platform (B. Haines, personal communication, 1997), space-borne special sensor microwave imager (SSMI) (V. Zlotnicki, personal communication, 1997), and the space-borne ERS-1 radiometer [*Kruizinga*, 1997]. Table 2 summarizes the long-term relative slopes between TMR and these data. The three slopes agree to within 0.1 mm yr^{-1}, implying a drift in the sea level measurement of about -1.9 mm yr^{-1}, which is highly suggestive of a drift in the TMR measurement. The sense of this drift would be to cause the TOPEX sea level to measure lower than the in situ data after a period of time, which is what is observed.

Table 2. Relative Drift Between TMR and Other Measurements of Water Vapor Path Delay

TMR Minus	Relative Drift
ERS-1 radiometer	-1.9 ± 0.5
SSMI	-1.8 ± 0.5
Harvest WVR	-1.9 ± 1.2

TMR is TOPEX mircrowave radiometer, SSMI is special sensor microwave imager, and WVR is water vapor radiometer. Units are in mm yr^{-1}.

3. Conclusions

This study corroborates the analysis by *Mitchum* [1998] that an averaged time series of differences between TOPEX and tide gauge measurements indicates that TOPEX sea level measurements are drifting away from the truth. The size of the drift is -2.6 ± 1.5 mm yr^{-1} when the TOPEX internal calibration is applied. Furthermore, additional evidence has been provided to support the conclusion that the relative drift is due mostly to a drift in the TOPEX measurements, based on the relative drift between TOPEX and TAO buoys in the eastern Pacific. The size and direction of the drift relative to the TAO data agree with the drift relative to tide gauges within the uncertainty.

The drift measured by the internal calibration does not explain the drift detected in the sea level measurement and, in fact, makes it more negative by -1.2 mm yr^{-1}. There is increasing evidence that the TMR may be drifting at the level of -2 mm yr^{-1}. This would explain most of the observed drift in the TOPEX measurement.

This analysis and that of *Mitchum* [1998] suggests that the tide gauge network can be used to provide a good estimate of altimeter drift at the level of 1 - 2 mm yr^{-1}. However, because the estimated error in this calibration is nearly as large as the estimated drift and because the size of the error is based on somewhat speculative terms (especially regarding the size of vertical motion at the tide gauges) we believe one should be cautious about applying these drift estimates to the TOPEX measurements to try to remove a drift in the altimeter. At most, we believe that they should be used as a measure of the uncertainty in any study of long-term sea level change measured with TOPEX data. To increase the accuracy of the method, more work needs to be done in determining or modeling systematic errors in the tide gauge data. The largest such error, vertical motion in the tide gauge data, could be reduced by monitoring vertical motion at the site with a Global Positioning System (GPS) receiver tied into a well-defined reference frame. While this calibration system will be more expensive than a calibration system at only one site, it appears to be the only method to realistically monitor mm yr^{-1} drifts in satellite altimeter measurements in the span of only a few years.

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D.P. Chambers, J.C. Ries, and B.D. Tapley, Center for Space Research, University of Texas, 3925 W. Braker Lane, Suite 200, Austin, TX 78759. (e-mail: chambers@crs.utexas.edu).

K.C.Shum, Department of Geodetic Science and Surveying Ohio State University, 470 Hitchcock Hall, 2070 Neio Ave., Columbus, OH 43210.

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