JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. C12, PAGES 25,101–25,108, DECEMBER 15, 1995

A comparison of coincidental time series of the ocean surface height by satellite altimeter, mooring, and inverted echo sounder

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Abstract. Altimetric measurements of sea surface height at two locations in the western tropical Pacific Ocean are compared to estimates of the dynamic sea surface height computed from cotemporal surface-to-bottom temperature/salinity measurements on moorings and acoustic travel time measured by bottom-moored inverted echo sounders. The results show statistically high correlation between the in situ measurements at periods greater than 5 days and between the altimeter and in situ measurements at periods greater than 20 days. The rms difference between any two modes of observation is consistently between 2 and 3 cm.

1. Introduction

The classical method of observing the sea surface height has been to make shipboard measurements of the vertical density profile and then calculating the dynamic surface height relative to a deeper reference surface. Beginning in the 1920s, the profile was estimated from sampling at a discrete number of depths with Nansen bottles, and by midcentury, better vertical resolution was achieved by lowering continuously sensing instruments. To obtain a time series at a site required the ship to either remain there or continuously revisit the site, and, understandably, few series were obtained.

Two methods (a moored vertical string of instruments and an inverted echo sounder [*Bitterman*, 1976]) were subsequently developed to obtain longer-time in situ measurements. The first of these is an extension of the discrete bottle hydrocast, but the second, which integrates acoustically over the water column, introduces a new variable. One purpose of this paper is to compare the results when coincidental observations are made by these two methods. This will be done at two sites in the western tropical Pacific.

The future, with satellite altimetry capable of providing a continuous, near-global observation of sea surface height, promises a change in how the oceans can be studied. However, it is first essential that the accuracy and possible limitations of altimetry be understood. The primary purpose of this paper is thus to compare the time variability of the dynamic height of the sea surface as determined from in situ measurements with coincidental altimeter observations.

Two Tropical Ocean and Global Atmosphere-Tropical Atmosphere Ocean (TOGA-TAO) moorings were deployed with additional instruments along 2°S to coincide with crossing points of two pairs of TOPEX/POSEIDON (T/P) paths at 156°E and 164°E. Three inverted echo sounders were deployed (two at 156°E). The exact locations and deployment/recovery dates are given in Table 1. The ocean depth at the two sites is 1.7 and 4.4 km, respectively. Their location in the Pacific and relative to the crossing satellite paths is shown in Figure 1.

The comparison is not thought to be particularly site-dependent. However, the location in the tropics is characterized by a large-amplitude M_2 tidal component (0.5 m) and only an average annual sea surface variation of 20 cm. These two conditions combine to make this a better than average location to evaluate the altimeter which relies on models of the tide to remove what would otherwise be severe tidal aliasing.

2. Data Description and Reduction

Each of the methods of observations responds differently (or not at all) to various time-dependent, vertical displacements in the water column. For example, individual instruments on the mooring (with sample rates as fast as 5 min) will sense the presence of internal gravity waves. They and the echo sounders will be influenced by the internal tides and inertial gravity waves. All are influenced by the barotropic tide but to a different extent, and comparison requires a special analysis. Some of these high-frequency signals are discussed by *Picaut et al.* [this issue], but our purpose here is to focus on their common window of observation. Quantitative comparison between the three modes of observation therefore requires appropriate low-pass filtering.

2.1. Moorings

The two moorings were deployed by the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL) and l'Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) laboratory in New Caledonia. They consisted of ATLAS moorings (10 temperature sensors which record

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Paper number 95JC01959.
0148-0227/95/95JC-01959$05.00

Table 1. Mooring and Sounder Locations

	Latitude, S	Longitude, E	Data Record Begins	Data Record Ends
		Observations at 156°E		
Mooring	1°59.2′	155°53.8′	Sept. 12, 1992	Feb. 22, 1993
IES (A)	1°59.2′	155°53.3′	Sept. 12, 1992	Feb. 22, 1993
IES (L)	1°59.6′	155°54.0′	Sept. 12, 1992	Dec. 7, 1992
		Observations at 164°E		
Mooring	1°59.4′	164°24.9′	Aug. 26, 1992	March 11, 1993
IES (L)	2°01.0′	164°24.4′	Aug. 26, 1992	March 22, 1993

IES is inverted echo sounding. A is Atlantic Oceanographic and Meteorological Laboratory sounder. L is Lamont-Doherty Earth Observatory sounder.

daily mean temperature between the surface and 500 m), augmented with (1) 5/12 (shallow/deep site) minitemperature recorders, below 500 m and approximately 500 m apart, recording at 5-min intervals; (2) 16/11 (shallow/deep site) SEACAT temperature-salinity sensors above 750 m, with sampling intervals mostly at 5 min; and (3) pressure recorded at four depths between 300 and 750 m (and from which the depth of each instrument was calculated) at 10-min intervals.

All the time series were first interpolated to common 5-min intervals, taking into account the high-frequency variations from the surrounding instruments. Salinity, where available, was interpolated to the bracketed temperature sensors (taking into account the vertical movement of each sensor). Below 750 m a mean temperature-salinity relationship was used to assign a salinity to the observed temperature. Each instrument was calibrated before and after the experiment, with little variation found. A linear interpolation in time was used to correct the final time series.

Table 2. Variance at the 164°E (Deeper) Site

	Range, mm	rms, mm
0/1000 dbar	229.8	48.0
0/4400 dbar	251.8	50.3

Surface dynamic height, relative to both 1000 dbar and the bottommost sensor, was computed after reducing each time series back to hourly averages. As might be expected, there is no significant difference in the variance between the two calculations (see Table 2).

With less than 5% of the time-variable signal in dynamic height originating below 1000 dbar, subsequent discussion is limited to surface height relative to that depth. However, both are shown in the Figure 2 (top) after low-pass filtering.

2.2. Inverted Echo Sounder

To calibrate the sounders, the recorded change in travel time δt is divided into two parts,

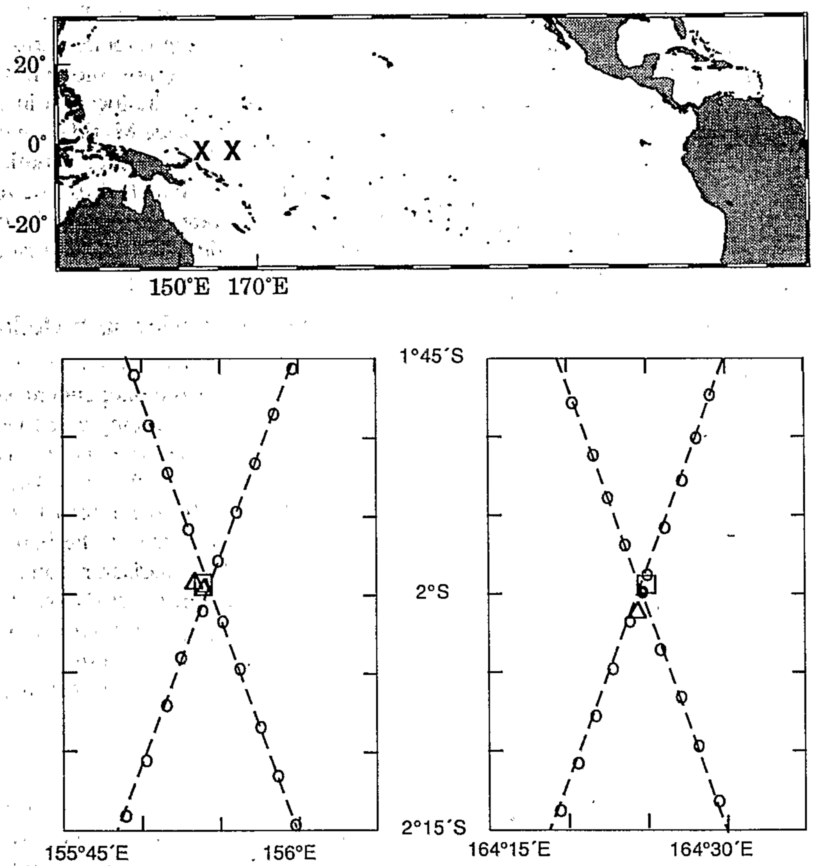

Figure 1. (top) Site locations. (bottom) Locations of moorings (squares), sounders (triangles), and altimeter tracks (dashed lines) for passes (left) 86 and 251 and (right) 60 and 225, which cross over the in situ observations. Discrete altimeter reports along a typical path are indicated by circles.

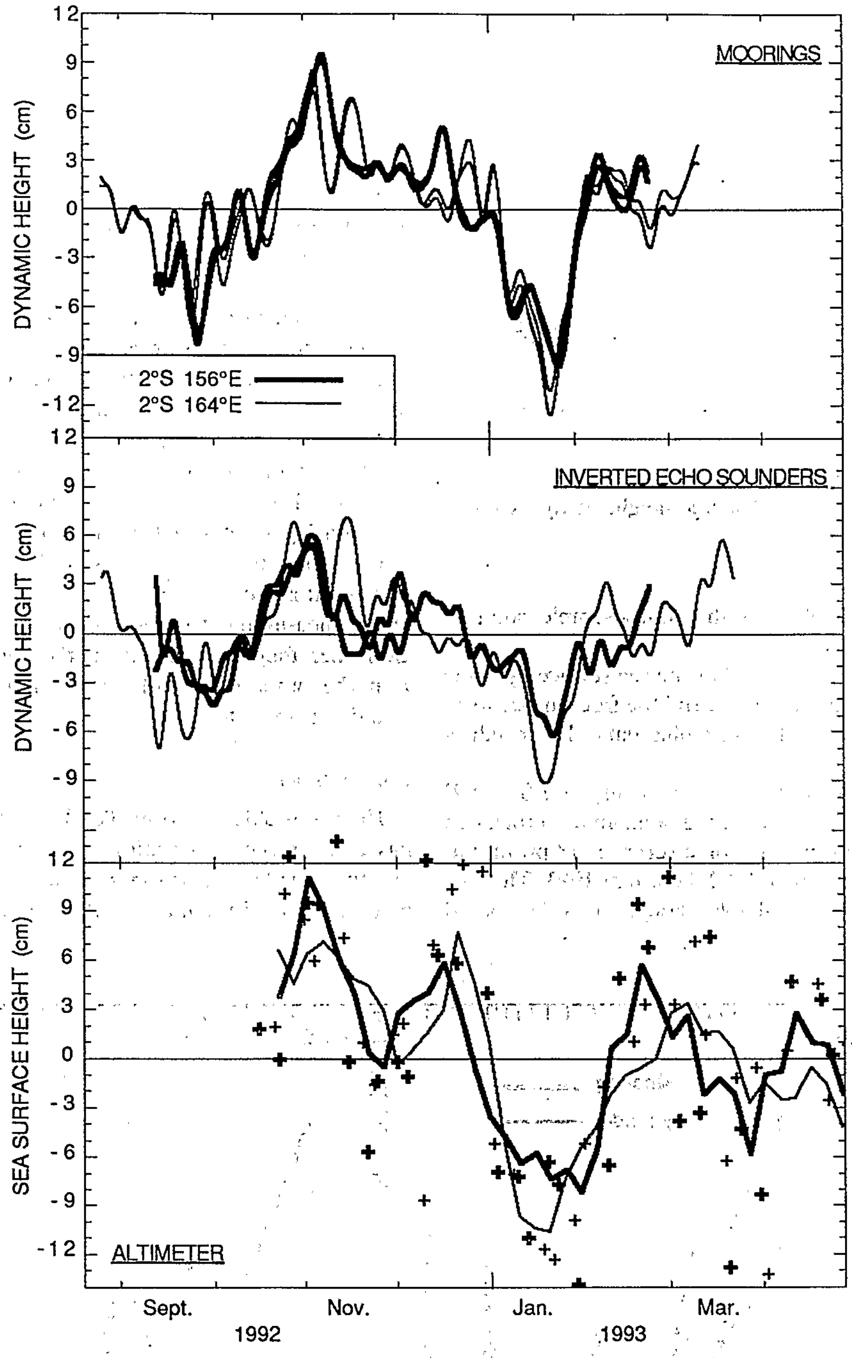

Figure 2. Time series of the observations. The mean of each series has been removed. (top) Data from the two moorings after 5-day, low-pass filtering. Both 0 relative to 1000 dbar and 0 relative to bottom are drawn, with only the slightest difference noticeable at the deeper site. (middle) Data from the three sounders after 5-day, low-pass filtering. After mid-December, only one of the sounders yielded data at 156°E. (bottom) Two representations of the altimeter data. Plus signs are the individual observations after processing, as described in the text. Solid lines are 20-day running mean averages computed every 5 days.

$$\delta t = \delta\left[\int_H^{z_0} \frac{dz}{c}\right]$$

$$\delta t = \left(\int_{z_r}^{z_0} + \int_H^{z_r}\right)\delta\left[\frac{1}{c}\right] dz,$$

where c is the sound velocity at depth z, z_0 is the free surface (defined as gage pressure = 0), H is the depth of the sounder, and z_r is the depth of a reference pressure level. Assuming z_r to be a level of no motion, the first term is computed from historical hydrocasts in the region and the second term is ignored. That latter term contains the following two possible signals: changes in the temperature of the deeper waters and barotropic changes in the sea surface height. Aside from the barotropic tide, both signals vary slowly relative to the baroclinically induced variability and are assumed to be uncorrelated with it. The barotropic tide, which is the largest part of

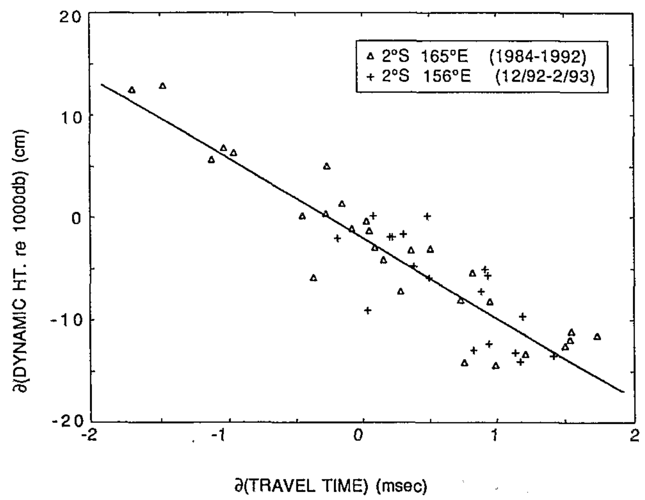

Figure 3. Regression of the dynamic height of the sea surface on acoustic travel time.

the sounder signal, is resolved by the hourly sample rate and then removed by a low-pass filter.

With a reference level of 1000 dbar the sea surface dynamic height and the travel time between it and the free surface were computed from two sets of hydrographic data. The result is shown in Figure 3.

One set consists of 30 profiles in the vicinity of 2°S, 165°E made from 1984 to 1991 (half during semiannual cruises in January and July). The other is a time series of 18 profiles at 2°S, 156°E made in December 1992–February 1993. The two sets are statistically indistinguishable, though the wider spread of data from 165°E reflects the fact that some of the observations were made during several strong, basin-wide, interannual events (the 1986/1987 and 1991/1992 El Niño episodes).

The slope of the regression line of the combined data set is −77.9 mm/ms with a standard error of 3.0 mm/ms. Confirmation that this regression coefficient is not time-dependent and is representative of an even larger geographic area comes from a comparison with the published results of *Maul et al.* [1988] in the eastern tropical Pacific. From 133 profiles referenced to 1000 dbar in the area 0.5°S–1.5°N, 105°W–115°W, they computed the statistically equivalent value of −73.4 (±2.1) mm/ms.

The derived regression is used to interpret the changes in total travel time recorded by the sounders after the sounders' time series were low-pass filtered. The resulting dynamic heights are shown in Figure 2 (middle). The two sounders at 156°E track one another well for the beginning of the record and then diverge. The Lamont sounder (L in Table 1) was experiencing reset problems (which may have disturbed its timekeeping and was soon to shut down the instrument completely). It is shown here only to demonstrate the repeatability of the measurement by two separate instruments for the 70 days when they both were properly sampling, but comparison with the other modes of observation will use only the A sounder at this site.

2.3. Altimeter

The first usable data from TOPEX/POSEIDON comes from passes over the observation sites on October 13, 1992, 2 months after launch and more than 1 month after the beginning of the in situ data. It is then continuously available for

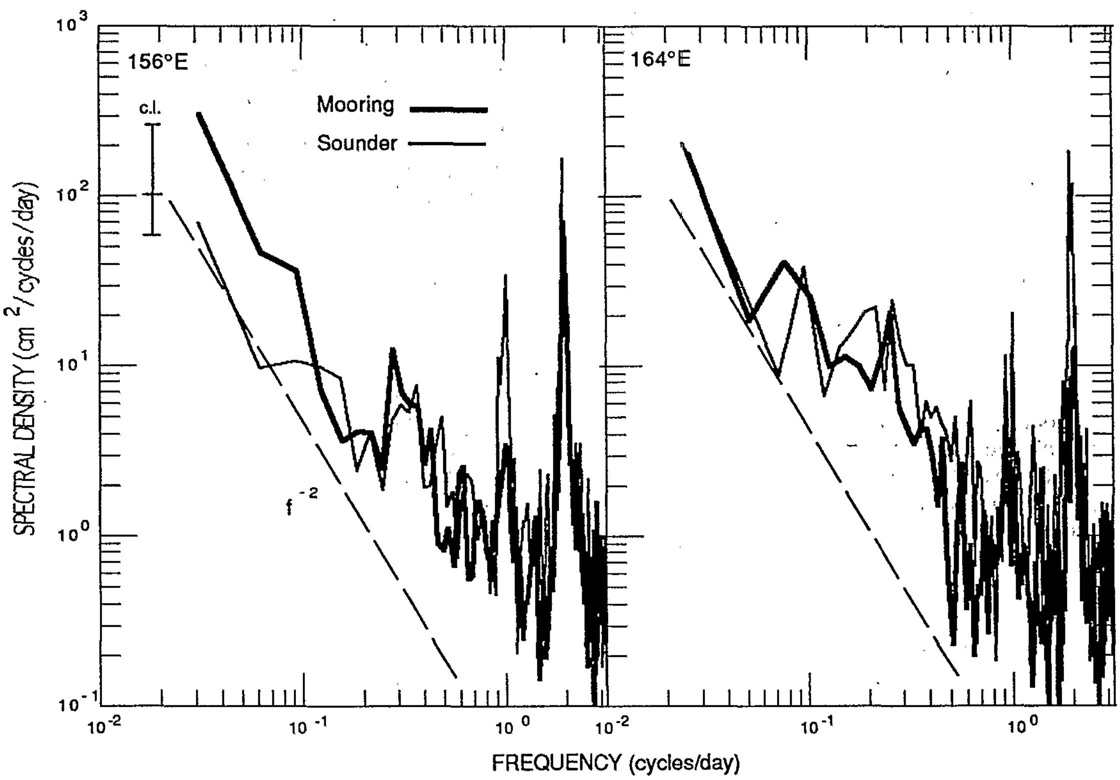

Figure 4. Estimates of spectral density of the sea surface height. Hourly data (except bihourly from sounder at 156°E) are averaged over five frequency bands. The (95%) confidence limit (cl) shown is for 15 degrees of freedom (see text).

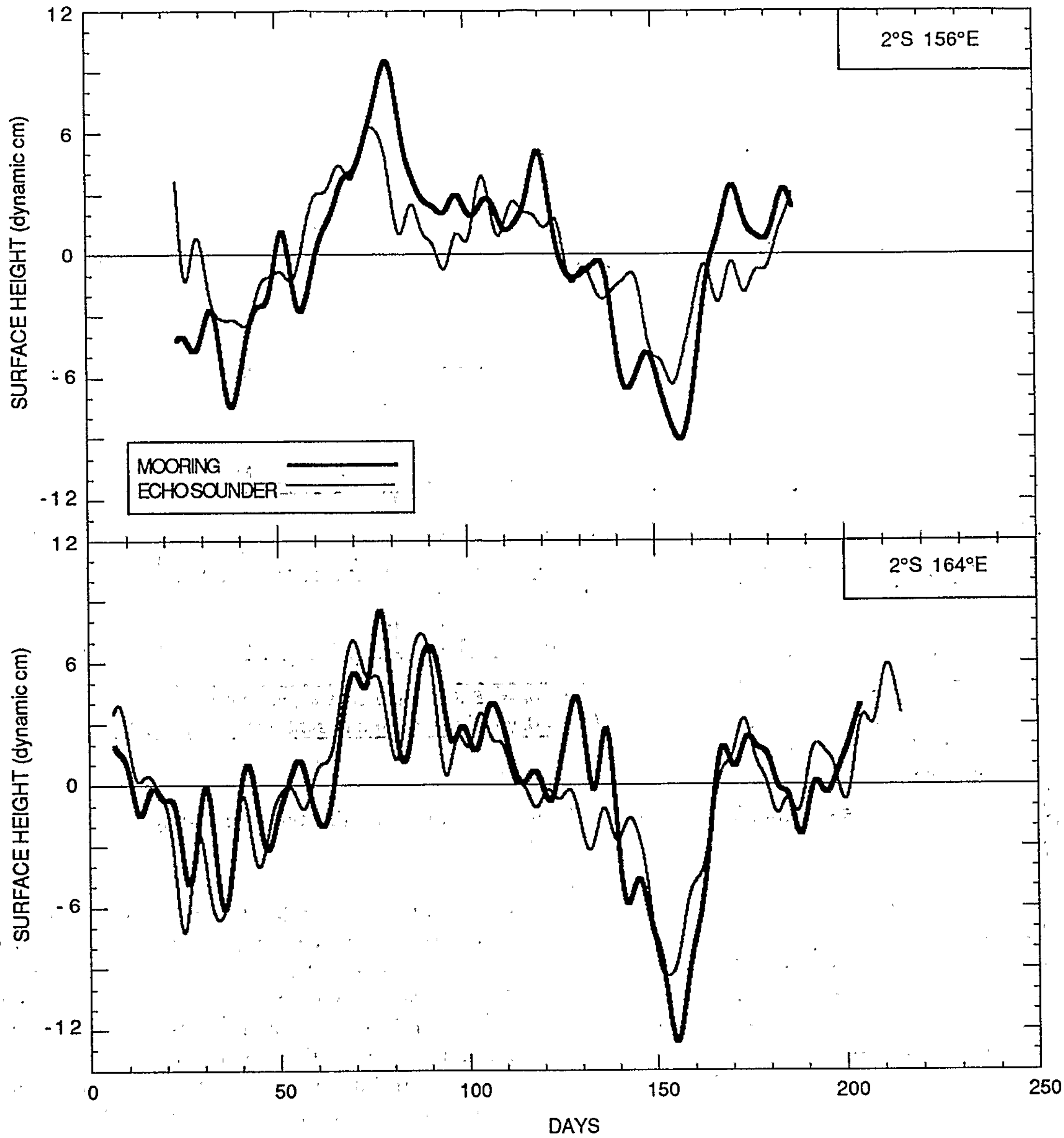

Figure 5a. Comparison of the in situ observations at both sites. Here Figure 2 (top and middle) is redrawn to show tracking between sounder and mooring.

each "10-day" cycle until after the in situ instruments were recovered. The location of the tracks relative to the observation sites is shown in Figure 1. The satellite reports data at a rapid rate which translates into 10 independent observations in a half-degree band of latitude about the site. To reduce some of the measurement noise (and possibly small-scale ocean variance), the surface height of the site is obtained by linear regression over the meridional band after occasional outliers are removed. The data going into that regression are exactly that obtained from the NASA merged geophysical data records (with corrections as recommended by [*Benada*, 1993] and using the NASA orbit) after subtracting 175 mm from the data of the occasional cycle when the POSEIDON altimeter is on to compensate for a reported instrument bias relative to the TOPEX altimeter.

Once the time series of each pass over each site were developed, two other adjustments were made before smoothing the data. First, the mean values of the time series were removed. This was done by pass and not by site because the mean values of the two passes over the 156°E site were found to vary by 140 mm, and this was thought to be an artifact of the introduction of the model geoid gradients along the two tracks. Second, the possibility of tidal aliasing had been taken into account. That is, if the tidal model used to remove the tide from the altimeter signal is not completely accurate, then there is a possibility of introducing a spurious signal (the accuracy of tide models is explored further in the appendix). For the M_2 tide (frequency f_{M_2} = 1.932227 cycles/d) which dominates the barotropic tide in this area and the TOPEX sampling frequency f_t of (9.9156 d/cycle)$^{-1}$, the alias frequencies f_a are given by

$$f_a = Nf_t - f_{M_2},$$

where N is an integer. Only N = 19 gives a frequency within the spectral window of the altimeter (a period of 62.1074 days, all other N yield periods of less than 12 days). Modulating each time series by e^{if_a} yielded amplitudes of 2.9 and 3.0 mm, and the time series were accordingly complex demodulated at that frequency.

Site		From:	To	Days	R.M.S.(mm)	X% of variance of Y in Z (X)	Y	Z	Coherence (R) between Y & Z
156°E									
Mooring vs.	A	9/12/92	2/22/93	163 *	26.9				
Sounder	M				41.5				
	M-A				25.6	62%	M	A	0.80 * 0.93 **
Sounder vs.	L	9/12/92	12/6/92	85 *	25.9				
Sounder	A				26.6				
	A-L				13.1	76%	A	L	0.81
Altimeter vs.	T	10/23/92	2/10/93	110 **	56.3				
Sounder	A				25.4				
	T-A				33.5	65%	T	A	0.94
Altimeter vs.	M				37.6				
Mooring	T-M				27.3	77%	T	M	0.91
164°E									
Mooring vs.	L	8/26/92	3/10/93	196 *	35.5				
Sounder	M				38.9				
	M-L				20.1	73%	M	L	0.86 * 0.95 **
Altimeter vs.	T	10/23/92	3/12/93	140 **	53.7				
Sounder	L				30.6				
	T-L				32.9	63%	T	L	0.84
Altimeter vs.	T	10/23/92	2/25/93	125 **	56.2				
Mooring	M				36.9				
	T-M				27.4	76%	T	M	0.91

A=AOML sounder
L=LDEO sounder
M=TOGA-COARE mooring
T=T/P altimeter

*Low-pass (5 days) and subsampled daily
** 20 day running mean and subsampled every 5 days

Figure 5b. Numerical correlation between in situ and altimeter observations.

As a final step, before comparing the altimeter with the in situ observations, the altimeter data are bin-averaged over 20 days every 5 days. This result is shown in Figure 2 (bottom), along with the unaveraged data. This last smoothing is to take into account that the altimeter data consist of two (unevenly spaced) observations every 10 days, and it is therefore unable to resolve periods shorter than 20 days.

3. Comparisons

3.1. Sounders Versus Moorings

The sounder and mooring measurements have much in common, differing primarily in the methodology used to compute the surface dynamic height. The former relies strongly on the stability of the temperature-salinity correlation to convert effectively a vertically averaged temperature, over the entire water column, into an integrated density measurement. The latter (which also depends on the temperature-salinity assumption below 750 m, where no salinity measurements were made) assumes that the vertical distribution of sensors was sufficiently dense and properly distributed to accurately record the vertical integral it calculates from a finite number of discrete points. The comparison between the two is indicative of the plausibility of their underlying assumptions where they differ.

In Figure 4 the estimates of spectral densities of sea surface height from the two in situ methods at the two sites are compared. They resemble each other in the following ways: the high-frequency end of the spectrum is dominated by the diurnal and semidiurnal tidal motion. At midfrequency, 3–5 day periods, there is an increase in variance from inertial gravity waves, as previously reported in the tropical Atlantic Ocean [*Garzoli and Katz*, 1981]. The low-frequency end (beginning at periods of 10–20 days) shows an f^{-2} behavior which, by extrapolation from 6-year records in the tropical Atlantic [*Katz*, 1993], would continue until the annual period. The quantitative comparisons between these observations and the altimeter will be restricted to this low-frequency band.

The spectral density at the lowest frequencies are identical for the two observations at 164°E and for the sounder at 156°E. The mooring at the latter site appears to be higher, but after noting that this is true for only the three lowest estimates, comparing their averages would give 3 × (5 frequency bands averaged) or 15 degrees of freedom. The 95% confidence limits for this are shown in Figure 4, and the average spectral estimates are found to be not significantly different.

To compare the moorings and sounders, the 5-day, low-pass filtered data of each are shown superimposed in Figure 5a. This filtering removes the high-frequency variations which enter differently into the two modes of observation. As noted in the spectral comparison, the observations at 164°E (the eastern, deep water site) track better at low frequency.

Some statistical measures of the comparisons are given in Figure 5b. The correlation coefficient between the two signals at 164°E (L and M) is 0.86. Subtracting the sounder data from the mooring data removes 73% of the variance. Both of these measures are comparable to the result from the sounder versus sounder record (L and A), suggesting that the mooring and sounder record the same signal to 2 cm (the rms of M − L), a number measuring the instrument/ocean noise of the two signals.

Unlike the comparison at 164°E, where mooring and sounder had rms values within 10% of one another, their rms

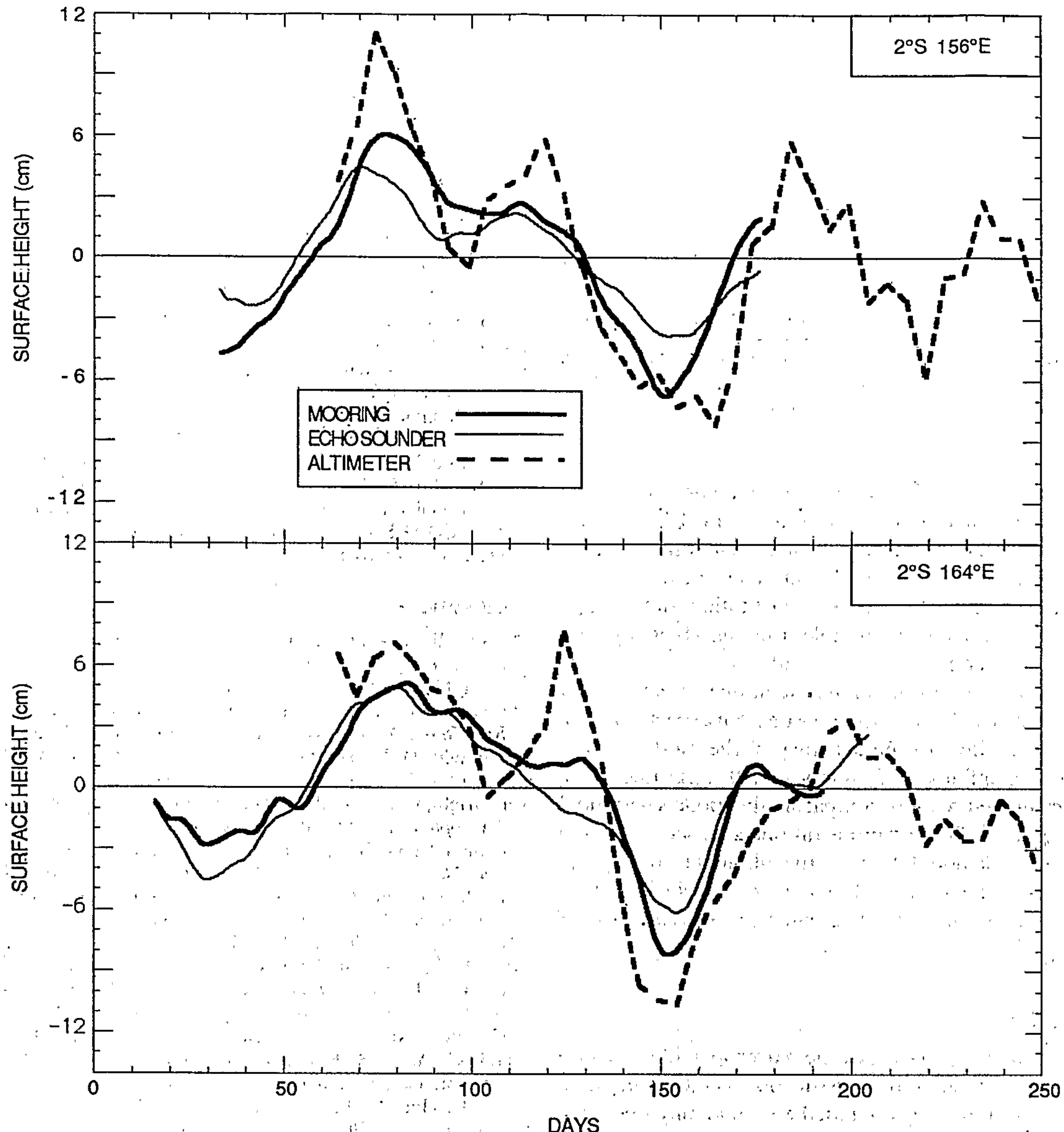

Figure 5c. Comparison of the three observations at both sites. A running mean average over 20 days is plotted every 5 days.

differ by 50% at 156°E. Yet the reduction of variance and rms of their difference (62% and 2.5 cm) are comparable.

3.2. Altimeter Versus Mooring/Sounder

To compare the altimeter to the in situ measurements, the data sets were averaged over 20-day periods. This was shown for the altimeter data in Figure 2 (bottom), and in Figure 5c it is compared with the mooring and sounder data after processing them with the same running mean filter. The statistics of this comparison are also given in Figure 5b.

The rms height of the altimeter data is always higher than either of the in situ observations, but 63 to 77% of its variance is also present in the latter. The correlation coefficients are high (0.84 to 0.94) and only slightly less than the mooring/sounder coefficient (0.93 and 0.95) at low frequency.

4. Summary and Conclusion

The usual method for demonstrating the validity of the calibration of inverted echo sounder records is to compare them with dynamic height calculations from occasional contemporary hydrographic profiles. For example, *Katz* [1987] reported a standard deviation of 2.9 dynamic cm from 17 independent samples (in the tropical Atlantic). However, since the sounder is essentially a continuous observation while the profile is a snapshot, there is an uncertainty to how much of that deviation derives from high-frequency variability that is necessarily smoothed out of the sounder record before making the comparison.

The comparison here between moorings and sounders is not degraded by a difference in sample rate. However, the rms difference between measurements (2.0 and 2.6 dynamic cm) has not substantially improved. We are left with an uncertainty of about 2 to 3 cm between various methods of estimating sea surface height in situ.

This result then provides a quantitative measure with which to assess how well the TOPEX/POSEIDON altimeter data tracks the sea surface height. (Here, as throughout, we assume that low-frequency barotropic changes are small enough to be ignored). In Figure 5b, four comparisons between altimeter

Table 3. Inverted Echo Sounder Derived Barotropic Tidal Constituents and a Bottom Pressure Sensor Compared With Two Tidal Models at 2°S, 164°E

	IES		Pressure Gauge		C/R		Schwiderski	
	a	*p*	*a*	*p*	*a*	*p*	*a*	*p*
O_1	71.0	38	91.8	39	91.9	36	84.4	41
K_1	136.4	49	157.6	54	151.9	54	146.5	62
N_2	104.8	142	109.3	139	107.4	144	91.2	144
M_2	469.2	148	526.0	139	522.4	141	482.7	142
S_2	254.6	153	297.5	152	270.5	150	275.0	157

IES is inverted echo sounder, C/R is the *Cartwright and Ray* [1990] model; Schwiderski is the *Schwiderski* [1981] model; *a* is amplitude in millimeters; and *p* is phase in degrees relative to Greenwich.

and in situ observations show an rms difference of 2.7 cm (compared with either of two moorings) and 3.3 cm (with either of two sounders). Thus we conclude that at the frequencies resolvable by the altimeter, the altimeter yielded a time-variable sea surface height (at our verification sites) at an accuracy statistically indistinguishable from our ability to measure that same variability by in situ methods.

Just as the orbit cycle time limits the altimeter data to low frequencies, it also makes the accuracy one can expect from the altimeter very sensitive to the accuracy of the models of the relatively large-amplitude but undersampled, local tides. The latter were evaluated both by comparing the models with tidal estimates from in situ observations (at one site; see appendix) and by complex demodulation of the altimeter time series themselves after the predicted tide was removed. Neither method indicated any uncertainty greater than the base level of 2 to 3 cm.

Appendix: Tides

As noted in the text, aliasing of the barotropic tides because of imperfect tidal models is an issue that needs evaluation. However, for the sites being discussed we found only a possible effect of no more than several centimeters. An inverted echo sounder record, as shown by *Cartwright* [1982], can, however, give an independent estimate of the tides. In Table 3 we compare the amplitude and phase of five major constituents from the sounder at 164°E with the two tidal models supplied with the altimeter data; namely, the *Cartwright and Ray* [1990] model, based on Geosat altimeter data, and the earlier *Schwiderski* [1981] model, based on a collection of shoreline tidal measurements. The sounder data were analyzed using the *Foreman* [1977] program with the assumption of a mean sound velocity of 1540 m/s at the sea surface. Also included in the comparison is a tidal analysis from a pressure gauge deployed by PMEL, NOAA, for the same time period and within 1 n. mi. (1 n. mi. = 1.852 km) of the sounder.

First, we note the good agreement between the in situ methods: at worst, a 5 cm difference in amplitude and less than 10° in phase. The largest difference is with the M_2 component, where the sounder may be influenced by baroclinic tides at that frequency. The comparison between the two in situ methods and the two tidal models indicates no large or systematic differences, confirming what was deduced from the altimeter record itself, which is that tidal aliasing could, at best, introduce an uncertainty of a few centimeters, even in this area of relatively large-amplitude, deep water tides.

D. E. Cartwright and R. D. Ray (personal communication, April 1994) have recently made available a revised model calculation based on early TOPEX/POSEIDON data. They do not suggest any substantial change at the locations of concern here. For example, the largest-amplitude constituent considered, M_2 at 164°E, is revised to 544.7 mm, 143°.

Acknowledgments. E. J. Katz would like to acknowledge the support of NASA (grants JPL 958123 and NAG 5-2058), Marcela Stern for collecting the data, and Miguel Maccio for assistance in analyzing the altimeter data. M. Bushnell thanks Dave Bitterman for his new design and construction of a low cost IES and Pamela Haines for her assistance in deployment and recovery. Mooring data were made possible through the support of NASA, CNES, ORSTOM, and NOAA. Additional SEACAT data from the mooring at 156°E were graciously made available to us by Roger Lukas, collected as part of a separate TOGA-COARE project. This is contribution 5373 from the Lamont-Doherty Earth Observatory.

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(Received September 23, 1994; revised June 26, 1995; accepted June 26, 1995.)