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***** Mark BUSHNELL

* ORSTOM, Nouméa
** NASA/GSFC, Greenbelt
*** NOAA/PMEL, Seattle
**** LDEO/Columbia University, Palisades
***** NOAA/AOML, Miami

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CENTRE DE NOUMÉA

/Picaut, J.
Busalacchi, A.J.
Mc Phaden, M.J.
Katz, E.J.
Gourdeau, L.
Gonzalez, F.I.
Hackert, E.C.
Bushnell, M.

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SOMMAIRE

RÉSUMÉ

Durant la période de vérification de la mission altimétrique franco-américaine TOPEX/POSEIDON, une expérience de validation rigoureuse des mesures altimètriques a été effectuée en plein océan dans l'ouest du Pacifique équatorial. Entre août-septembre 1992 et février-mars 1993, deux mouillages du réseau multinational TOGA-TAO situés à 2°S-156°E (profondeur 1739 m) et à 2°S-164,4°E (profondeur 4400 m) ont été équipés de capteurs supplémentaires de température, salinité et pression afin de mesurer très précisément, toutes les cinq minutes, les hauteurs dynamiques de la surface jusqu'au fond, juste sur deux points de croisement des traces au sol du satellite TOPEX/POSEIDON. Parallèlement, des écho sondeurs inversés et des capteurs de pression ont été déployés sur le fond à proximité des deux mouillages. Une étude préliminaire à cette expérience de validation, confirmée par la suite, utilisant des mesures effectuées avec des sondes CTD de la surface jusqu'au fond, montre que l'ensemble des instruments le long des deux mouillages permet de mesurer les fluctuations des hauteurs dynamiques de surface avec une précision de 1 à 2 cm dyn. Cette expérience de validation a aussi bénéficié de données très complètes collectées dans cette même région durant la Période d'Observations Intensives du programme international TOGA-COARE entre novembre 1992 et février 1993.

Les fluctuations des hauteurs dynamiques de surface par rapport au fond, observées à partir de ces mouillages, ont un écart type de 5 cm avec des maximums de +/- 15 cm dyn. Une variabilité importante du niveau stérique de la mer a été mise en évidence à des échelles de temps situées entre quelques heures et quelques jours, principalement avec l'existence de fortes marées internes quasi permanentes. De telles marées internes entraînent des changements des hauteurs dynamiques de surface avec un écart type de 2 cm dyn. Au moins profond des deux sites de mesures (2°S-156°E), une déformation non linéaire probable des marées internes, observée de manière occasionnelle, peut entraîner des changements des hauteurs dynamiques de surface allant jusqu'à 30 cm dyn en moins d'une heure. Pour des échelles de temps supérieures au cycle de 10 jours du satellite TOPEX/POSEIDON, les fluctuations basse fréquence des hauteurs dynamiques sont reliées aux variations interannuelles correspondant à l'ENSO de 1991-93, au cycle

saisonnier et aux variations intrasaisonnières associées aux oscillations de 40-50 jours du champ de vent zonal équatorial.

Les comparaisons instantanées entre les mesures moyennes sur une seconde des altimètres de TOPEX/POSEIDON et les mesures toutes les cinq minutes des hauteurs dynamiques de surface ont été effectuées en rapport avec différent modèles de marée, la marée barotrope mesurée au fond, la pression de surface issue du modèle atmosphérique de l'ECMWF et la pression de surface mesurée à proximité d'un des deux mouillages. Selon le choix d'altimètre et des corrections appliquées aux données altimétriques, les différences rms entre les mesures satellitaires et in situ du niveau de la mer sont aussi faibles que 3,3 cm à 2°S-156°E et 3,7 cm à 2°S-164,4°E. Si l'on inclut suffisamment de données satellitaires supplémentaires au voisinage des mouillages, et après utilisation d'un filtre haute fréquence sur 30 jours, les données satellitaires et les mesures des hauteurs dynamiques de surface se trouvent fortement corrélées, avec des coefficients de corrélation voisin de 0,95 et des différences rms autour de 1,8 cm.

Les hauteurs dynamiques de surface, déduites des mesures le long des lignes de mouillages et du temps de parcours acoustique mesuré par les écho sondeurs inversés situés sur le fond, sont fortement corrélées pour des échelles de temps supérieures à cinq jours. Pour des échelles de temps supérieures à 20 jours, les très bonnes corrélations précédentes entre les hauteurs dynamiques de surface mesurées par les mouillages et les mesures altimétriques se retrouvent avec les hauteurs dynamiques de surface déduites des écho sondeurs inversés.

OPEN-OCEAN VALIDATION OF TOPEX/POSEIDON SEA LEVEL IN THE WESTERN EQUATORIAL PACIFIC

Joël Picaut
Groupe SURTROPAC,
L'Institut Français de Recherche Scientifique
pour le Développement en Coopération (ORSTOM)
Nouméa, New Caledonia

Antonio J. Busalacchi
Laboratory for Hydrospheric Processes
NASA Goddard Space Flight Center
Greenbelt Maryland

Michael J. McPhaden
NOAA Pacific Marine Environmental Laboratory
Seattle, Washington

Lionel Gourdeau
Groupe SURTROPAC,
L'Institut Français de Recherche Scientifique
pour le Développement en Coopération (ORSTOM)
Nouméa, New Caledonia

Frank I. Gonzalez
NOAA Pacific Marine Environmental Laboratory
Seattle, Washington

Eric C. Hackert
Laboratory for Hydrospheric Processes
Hughes STX Corporation
NASA Goddard Space Flight Center
Greenbelt, Maryland

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ABSTRACT

During the verification phase of the TOPEX/POSEIDON radar altimeter mission a rigorous open-ocean validation experiment was conducted in the western equatorial Pacific Ocean. From August-September, 1992 to February-March, 1993 two TOGA-TAO moorings at 2°S-156°E (1739 m depth) and 2°S-164.4°E (4400 m depth) were outfitted with additional temperature, salinity, and pressure sensors to measure precisely the dynamic height from the surface to the bottom at 5 min intervals directly beneath two TOPEX/POSEIDON crossovers. Bottom pressure gauges and inverted echo sounders were deployed as well. A predeployment design study using full depth CTD casts, subsequently confirmed by post deployment analyses, indicated this suite of instruments was capable of measuring sea surface height fluctuations to within 1-2 cm. The validation experiment also benefited from the comprehensive set of ocean-atmosphere measurements that were made in the region during the TOGA-COARE Intensive Observation Period of November 1992 - February 1993.

The surface relative to bottom dynamic height fluctuations observed in situ during the 6-7 month experiment had a standard deviation of 5 cm with excursions of order +/- 15 cm. Energetic steric sea level variability was found to exist on short time scales of order hours to a few days, most notably the quasi permanence of strong semi-diurnal internal tides. Such internal tides were noted to induce changes in surface dynamic height with a standard deviation of 2 dyn cm. At the shallower of the two sites, 2°S-156°E, a possible nonlinear rectification of the internal tide was observed occasionally to change the dynamic height by as much as 30 cm over less than an hour. On time scales longer than the 10 day repeat of the TOPEX/POSEIDON satellite, the low-frequency fluctuations of dynamic height were related to interannual variations corresponding to the 1991-93 ENSO, to the seasonal cycle and to intraseasonal variations associated with the 40-60 day oscillations of the equatorial zonal wind field.

Instantaneous comparisons between the 1 sec TOPEX/POSEIDON altimeter retrievals and the 5 min dynamic height were performed with regard to several tide models, the barotropic tide measured in situ, ECMWF surface air pressure, and the surface air pressure measured in situ. Depending on the choice of altimeter and of the environmental corrections applied to the altimeter data, the rms differences between the satellite and the in situ measurements of sea level were as low as 3.3 cm at 2°S-156°E and 3.7 cm at 2°S-164.4°E. When additional satellite data in the general vicinity of the mooring are included, and after the use of a 30-day low-pass filter, the satellite and in situ data were found to be highly correlated, with correlation coefficients of about 0.95 and rms differences around 1.8 cm.

1. INTRODUCTION

The initial results from the TOPEX/POSEIDON radar altimeter mission are very encouraging with respect to the capability of the altimeter to describe the sea level attributes of the large-scale ocean circulation (cf., J. Geophys. Res., special TOPEX/POSEIDON issue, 1994). Prior to launch, the precision of the radar altimeter instrument was projected to be of order 2.4 cm (TOPEX/POSEIDON Science Working Team, 1991). In the event this level of precision is attained in orbit, and the necessary environmental corrections are of similar order and result in an overall level of accuracy of order 4 cm, this class of radar altimeters will have considerable potential for long-term ocean climate monitoring. Thus, there is a clear need to rigorously validate the accuracy of TOPEX/POSEIDON sea level observations in the open ocean. Unfortunately, an open-ocean validation was not planned by the TOPEX/POSEIDON project. During the verification phase of the mission, the project sponsored calibration and validation experiments at Harvest Platform in the coastal waters off California and on the island of Lampedusa near Sicily (TOPEX/POSEIDON Joint Verification Team, 1992). These efforts were directed more towards validating the altimeter range delay between the satellite and the sea surface, than with characterizing the TOPEX/POSEIDON accuracy when monitoring open-ocean sea level variability.

Any attempt to validate TOPEX/POSEIDON in the open ocean is complicated by the fact that the intrinsic error of most in situ sea level estimates is of order 3 to 7 cm. The range of these errors depends on the particular measurement technique and its inherent limitations. For example, sea level deduced from island tide gauges is contaminated by interactions between the island and local currents, shelf effects, and wind set up. Dynamic height time series obtained from moorings, ship of opportunity expendable bathythermographs (XBT), conductivity-temperature-depth (CTD) casts, and inverted echo sounders (IES) are used to estimate the steric sea level contribution. The significance of the sea level estimated from these instruments and platforms is constrained by technical issues such as the reference level, the use of a mean temperature-salinity relation, and inadequate space-time sampling. Therefore, there is a fundamental difference between the anticipated TOPEX/POSEIDON accuracy and any present observational means for in situ validation.

Here, we present the results from a field experiment that was carefully designed for the expressed purpose of using in situ observations to validate open-ocean TOPEX/POSEIDON altimeter retrievals in the western equatorial Pacific during the 6-month verification phase. The validation of TOPEX/POSEIDON sea level in the equatorial Pacific Ocean is of particular interest because of the important climatic impact of changes in the tropical Pacific Ocean circulation related to the El Niño/Southern Oscillation (ENSO) phenomenon. Although the GEOSAT altimeter was capable of resolving the order 20 cm changes in sea level associated with the 1986-87 El Niño (Miller et al., 1988), considerably better accuracy is required to detect significant attributes of the seasonal and interannual variability of the tropical Pacific Ocean. The order 2-4 cm accuracy expected from TOPEX/POSEIDON is required if there is to be any hope of monitoring the tropical Pacific seasonal cycle of sea level (of order 5 cm standard deviation, McPhaden et al., 1988), quantifying the variability of low-latitude surface currents (Picaut et al., 1990), diagnosing western boundary wave reflections thought to be important in ENSO mechanisms such as the delayed action oscillator (Boulanger and Menkes, 1995), or initializing ENSO prediction models (Fischer et al., 1994).

The platforms used for this validation experiment consisted of two ATLAS moorings of the TOGA-Tropical Atmosphere Ocean (TAO) Array (Hayes et al., 1991). The TAO Array was implemented as part of the 10-year Tropical Ocean and Global Atmosphere (TOGA) Program for studies of seasonal to interannual climate variability, the most prominent mode of which is the ENSO phenomenon. TOGA-TAO has expanded from a few sites at the start of TOGA in 1985 to an array that presently consists of approximately 70 moorings spanning the tropical Pacific between 8°N and 8°S, 95°W to 137°E (McPhaden, 1993).

The two validation moorings used in this study were specifically situated directly beneath TOPEX/POSEIDON crossovers at 2°S-156°E and 2°S-164.4°E (Figure 1). On these two moorings, additional dedicated sensors were deployed (August-September, 1992 to February-March, 1993) based on a design study estimated to yield sea level with a 1-2 cm accuracy. Temperature and salinity sensors were added to the mooring line, from the surface to the bottom, to estimate the steric part of changes in sea level. Inverted echo sounders were deployed as independent measures of the steric variability. Bottom pressure sensors were deployed to determine the barotropic component and atmospheric pressure sensors were deployed to account for the inverse barometric effect.

The site for this validation experiment was based on the availability of additional in situ measurements in the region. Historical hydrographic information exists around the 2°S-164.4°E site because numerous cruise data (mostly from the French SURTROPAC program and the US/PRC bilateral program) and ATLAS mooring data have been collected there since 1985. The hydrographic data collected at this site were used to evaluate GEOSAT in 1986-87 (Delcroix et al., 1991) and to design the vertical array of sensors used in this experiment. The 2°S-156°E ATLAS mooring, installed in September, 1992 has the advantage of being located at the center of the TOGA Coupled Ocean-Atmosphere Response

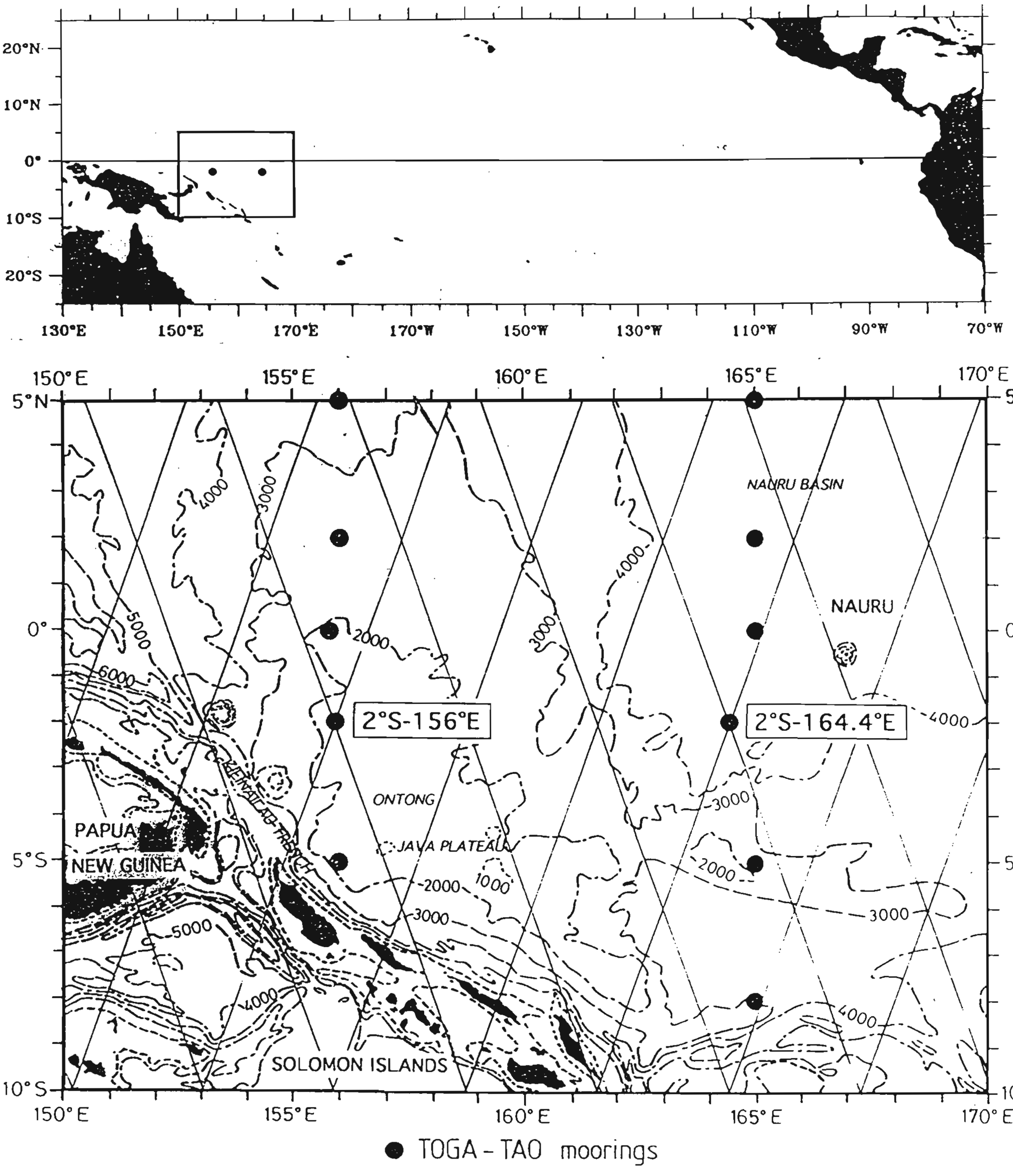


Figure. 1. Location of the two TOGA-TAO validation moorings. Superimposed are TOPEX/POSEIDON tracks and bathymetry contours in meter.

Experiment (COARE) Intensive Flux Array. This array provided unprecedented ocean-atmosphere measurements (e.g., temperature, salinity, currents, turbulence, wind, rain, pressure, humidity, radiation) during the experiment's Intensive Observation Period (November, 1992 - February, 1993) and was designed to study the interactions between the ocean and the atmosphere within the western Pacific warm pool region (Webster and Lukas, 1992). The suite of observations from ships, moorings, drifters, islands, aircraft, and satellites provides a tremendous opportunity to place the point measurements of sea level at the TOPEX/POSEIDON crossovers in a larger regional context. Lastly, the two mooring sites were located in very different geographical settings. The 2°S-164.4°E mooring was anchored on an abyssal plain (4400 m) far from a coast, whereas the 2°S-156°E mooring was situated on the Ontong Java Plateau (1750 m) near the Kilinailau trench and a little more than a first baroclinic mode radius of deformation (400 km) from New Ireland and Bougainville islands. The sea level comparisons between these two sites permit the quality of the TOPEX/POSEIDON retrievals to be interpreted with regard to the barotropic and baroclinic variability of two different depth regimes.

The present study complements a number of related studies of TOPEX/POSEIDON observations across the tropical Pacific Ocean. Previously, Busalacchi et al. (1994) compared the large scale spatial structure of sea level observed by TOPEX/POSEIDON during the first 17 months of the mission with gridded fields of dynamic height from the entire TOGA-TAO array for 8°N-8°S and 95°W-137°E. Although an examination of the basin-scale variability was possible in that study, a quantitative point-wise intercomparison was precluded by the distribution of the TOPEX/POSEIDON ground tracks relative to the TAO mooring locations as well as the time/space decorrelation scales used in the optimal interpolation technique. Here, we focus more on the time domain and thereby complement this previous examination of the spatial structure (more recently expanded upon by Menkes et al., 1995). A related paper by Katz et al. (1995) describes the processing and analysis of the inverted echo sounder subset of observations taken as part of this experiment, and the validity and limitations of this particular measurement technique when used to estimate changes in sea surface height.

The purpose of this paper is to present what may be one of the most precise estimates of sea level variability ever obtained in the open ocean. These in situ measurements of sea level are compared against instantaneous and low-pass filtered observations from TOPEX/POSEIDON, and placed in the context of the larger regional scale variability. Discrepancies between the in situ and satellite measurements are described in terms of the physical processes at work in the area, the spectral content of the oceanic signal that TOPEX/POSEIDON is subsampling, and the environmental corrections needed to process the altimeter data. In section 2 the experimental design and the manner in which the data were processed are presented. The nature of the in situ variability observed at the two mooring sites is described in section 3 in terms of the regional context, the high frequency variability, and low frequency fluctuations. Section 4 follows with the intercomparison of the TOPEX/POSEIDON sea level variability with that observed in situ. Discussion and conclusions are presented in section 5.

2. The Experiment, Data processing

This section summarizes the experimental design, instrumental configuration, operations at sea and data processing for our validation experiment. More detailed information can be found in a corresponding technical report (Gourdeau et al., 1995).

2.1. *Experimental design*

The ATLAS moorings (Hayes et al., 1991) are currently equipped with wind, air temperature, relative humidity and sea surface temperature (SST) sensors, a thermistor chain composed of 10 temperature sensors (25-500 m) and two pressure sensors (300 and 500 m). The number and vertical distribution of additional temperature and salinity sensors along the mooring lines were determined through a sampling study based on 13 and 57 deep CTD casts made from 1984 to 1990, respectively at and near 2°S-165°E. Surface dynamic heights relative to the bottom were calculated from a series of discrete T, S points subsampled from the CTD profiles at the sensors' depths and compared with their values using the complete CTD profiles. Different calculations, made with various array designs, resulted in an estimated standard error of less than 1 dyn cm for the array used at sea. Because of important salinity variations in the first 500 m (Delcroix et al., 1987), 10 thermosalinograph Seacat units were needed mid-way between pairs of standard ATLAS temperature sensors. Salinity at the ATLAS temperature sensors was computed by vertically interpolating the Seacat time series. From 500 m to the bottom (1739 m at 2°S-156°E; 4400 m at 2°S-164.4°E), water mass variations are small enough to use one Seacat at 750 m and several mini temperature recorders (MTRs). Salinity at the MTR depths was obtained by using a mean T-S relationship.

2.2. *Instruments*

Two ATLAS moorings at 2°S-156°E (1739 m depth, on the Ontong Java Plateau) and 2°S-164.4°E (4400 m depth, in the abyssal plain) were deployed respectively from 11

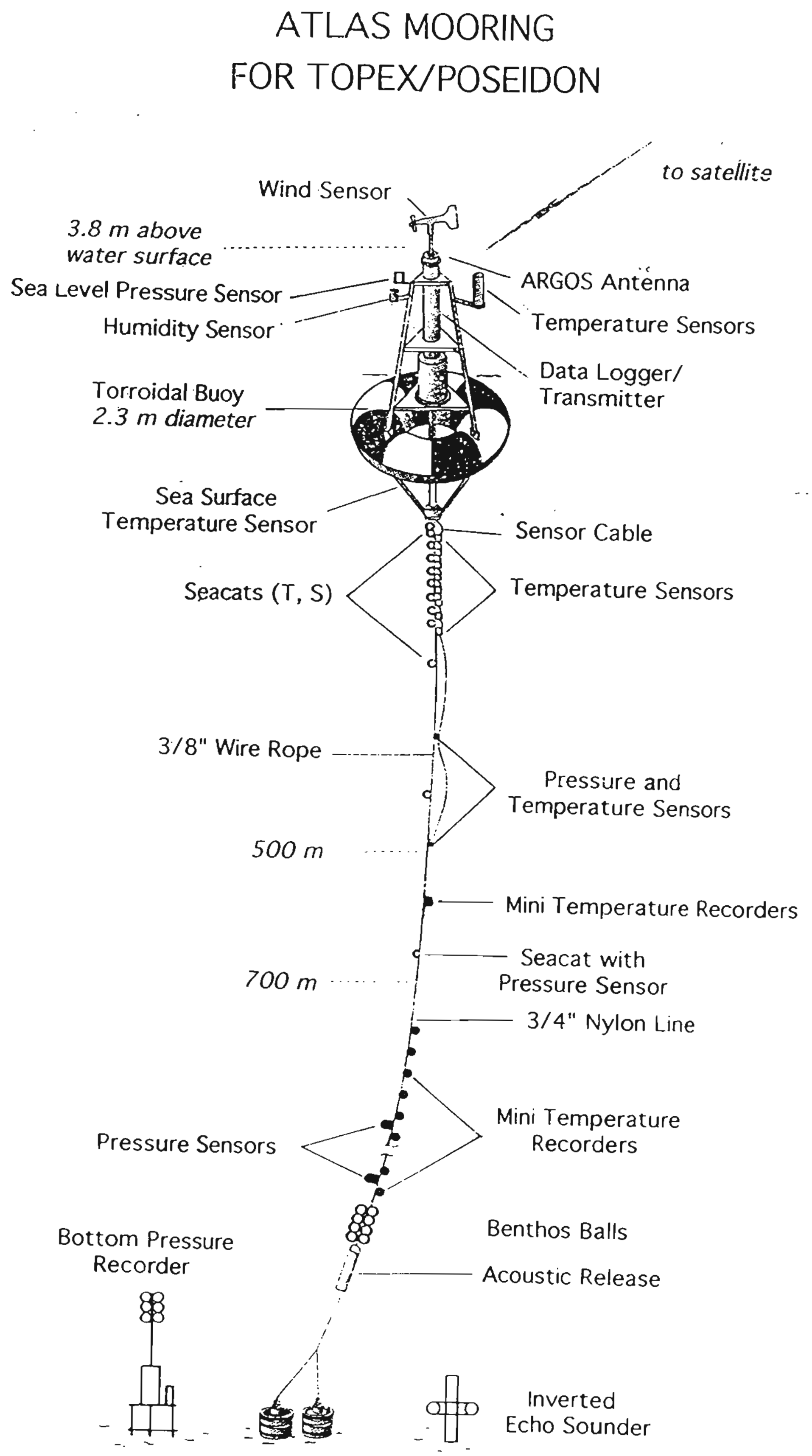


Figure 2. ATLAS mooring design with additional instruments along the line (Seacats, Mini Temperature Recorders, Benthos glass balls), and on the bottom Inverted Echo Sounder and Bottom Pressure Recorder.

September 1992 to 22 February 1993, and from 26 August 1992 to 22 March 1993. In addition to the standard ATLAS sensors, the following instruments were installed (Figure 2):

- on the surface buoy: 1 Aanderra surface pressure recorder at 2°S-156°E and 2°S-164.4°E.
- along the lines: 16 thermosalinographs Seacat (SB-16) at 2°S-156°E (2 with pressure sensors), 11 Seacats at 2°S-164.4°E (2 with pressure sensors), 5 MTRs at 2°S-156°E, 12 MTRs at 2°S-164.4°E, 1 Aanderaa recorder (pressure and temperature) at 2°S-156°E, 2 Aanderaa recorders at 2°S-164.4°E.
- on the bottom: 1 BPR (Bottom Pressure Recorder) at 2°S-156°E, 1 BPR at 2°S-164.4°E, 2 IES (Inverted Echo Sounder) at 2°S-156°E, 1 IES at 2°S-164.4°E.

The greater number of Seacats on the ATLAS at 2°S-156°E was due to the addition of 8 instruments provided by R. Lukas (University of Hawaii) as part of a COARE proposal to study the upper ocean thermohaline structure in the western equatorial Pacific.

2.3. *Data Processing*

On the 2°S-156°E mooring, no data were returned by one Seacat (45 m), and two Seacat data records were interrupted after 2 months of measurements (5 m and 30 m). On the 2°S-164.4°E line, one Seacat time series was interrupted after 2 months (137 m) and the temperature sensor of the Seacat at 400 m failed after one month. At 2°S-164.4°E, the MTRs stopped 10 days prior to recovery, and no data were returned by two of the 17 MTRs. For those instruments with complete records, pre- and post-deployment calibration differences were characterized by mean and standard deviation values, respectively, of -0.0013 and 0.0016 °C for Seacat temperature, 0.0063 and 0.0227 psu for Seacat salinity, and 0.0042 and 0.0057 °C for MTR temperature. The small difference between the pre- and post-calibrations of each sensor were used to correct the time series through a simple linear interpolation in time.

Due to an unprotected memory battery drain, all Aanderaa pressure and temperature data were lost. Continuous (7.5 min sampling) surface sea level pressure within 15 nautical miles of the 2°S-156°E ATLAS mooring was made available from October 21, 1992 to March 4, 1993 by R. Weller (Woods Hole Oceanographic Institution) as part of a COARE proposal to study air-sea flux exchange from the IMET (Improved Meteorological Package) mooring.

Since our experiment was based on the determination of accurate surface dynamic heights from the two moorings, a very careful subjective and objective data editing was undertaken. Most of the Seacat sensors had the same sample rate (5 min) as the MTRs. A few Seacat datasets (e.g., those with pressure sensors) had a sample rate of 10, 20 or 30 min. These were interpolated to a common 5 min sampling, using a technique which took into account the high frequency information from the surrounding Seacat sensors. The 10 ATLAS thermistor chain sensors provide daily mean temperature in real time; they were interpolated to the common 5 min sample rate through another similar technique which took into account the high frequency information from the Seacat sensors surrounding each ATLAS temperature sensor. Interrupted data records from a few sensors were extrapolated and interpolated in time using a combination of the initial data and the information from surrounding sensors (Gourdeau et al., 1995).

All of the sensors on the mooring lines were subject to vertical displacement mainly due to horizontal motion of the buoy (e.g., low frequency currents, tidal motion). At 400 m (750 m) the standard deviation of the vertical excursion was 2 m (4 m) with occasional extreme excursions of 6 m (15 m). Knowing that these vertical displacements may introduce additional error in the final dynamic height calculations, they have been taken into account at each sensor location by estimating the shape of the mooring line using the pressure sensors at 300, 400, 500 and 750 m.

For the sensors without conductivity (standard ATLAS and MTR), the salinity in the first 750 m was deduced from the surrounding Seacats, and below 750 m a mean T-S relationship was used. The mean T-S at the two sites were constructed from the mean of 57 surface-to-bottom CTD casts taken from 1984 to 1990 around 2°S-164.4°E, and from the mean of the 18 CTD casts taken from surface-to-bottom at 2°S-156°E during the repetitive 5°N-5°S COARE-POI (Période d'Observations Intensives) cruise (Eldin et al., 1994). The net result of processing these data sets was temperature, salinity and depth time series every 5 min at 28 levels from September 12, 1992 to February 22, 1993 (163 days) for the 2°S-156°E mooring (1739 m depth), and at 32 levels from August 26, 1992 to March 11, 1993 (197 days) at 2°S-164.4°E (4400 m depth).

An estimate of the different errors entering in our final surface dynamic height calculations was determined. It was based mainly on a sensitivity study using the 18 CTD casts made at 2°S-156°E during the COARE-POI cruise. The CTD casts were collected between December 8, 1992 and February 23, 1993, a period which encompassed half of the time of our validation experiment. Additional error calculations were also done using the mooring data after their processing. The resulting 1.1 dyn cm total error at 2°S-156°E (Table 1) is probably underestimated if applied at 2°S-164.4°E, given the coarse resolution of the sensors over a larger depth (4400 m compared to 1739 m) and the imprecise determination of

TABLE 1. Error budget at 2°S-156°E.

type of error	rms dif. (dyn cm)
vertical sampling	0.9
derived salinity	0.4
instrumental	0.4
vertical displacement	0.3
Σ baroclinic	1.1

vertical displacements of the sensors below the last 750 m pressure sensor (Gourdeau et al., 1995). However, given the small dynamic height signal at great depth (cf. section 3), and in view of the numbers in Table 1, the error in surface dynamic height at 2°S-164.4°E is likely to be of the order of 1.5 dyn cm.

The BPR systems acquire average pressure each 15 s, and have been used to measure tsunamis, tides, and seasonal phenomena to an accuracy of 1 mm equivalent seawater head at instrumental depths of 6000 m (Eble and Gonzalez, 1991; Boss and Gonzalez, 1994). Calibration is highly stable; BPR-derived tidal constituents at one station were shown to be constant for more than five years (Mofjeld et al., 1995). The pressure time series was edited, converted to equivalent water levels by using vertically averaged local density and gravity values, subjected to a Lanczos-square 2-hour low-pass filter, subsampled to provide hourly values, and harmonically analyzed for 59 tidal constituents (Foreman, 1977). Because accurate tide estimates are key to this experiment, we performed direct tests of potential errors introduced by filtering, hourly subsampling, and instrumental drift apparent in the initial portion of the time series. A test series was generated of unit amplitude, 15 s sampling, and 3.1 hr period (the shortest period constituent in our tidal analysis, M8). Filtering left the amplitude and phase unchanged; hourly subsampling and harmonic analysis produced a constituent amplitude reduced by 12 %. Since all constituents with periods less than 8 hours possessed amplitudes smaller than 3 mm, the effect of the filtering and subsampling was negligible. We then modeled and removed an exponential drift function fit to the data (Watts and Kontoyiannis, 1990), and a second tidal analysis produced tidal constituents essentially identical to the originals. However, the difficulty in removing the instrumental drift compromised the determination of the low frequency geophysical signal.

2.4. *TOPEX/POSEIDON Data*

The TOPEX and POSEIDON altimeter data and their environmental corrections used in this study come from an enhanced Geophysical Data Record (GDR) produced by the NASA/GSFC ocean altimetry group (C. Koblinsky). In this data set the GDR for the TOPEX and POSEIDON altimeters have been interpolated every 6 km to fixed points along track, and referenced to the location of the cycle 17 ground track. Since no altimetric measurement was made exactly over a mooring site, a maximum of eight TOPEX/POSEIDON retrievals nearest to the two mooring sites were used (i.e., four along descending and four along ascending tracks and within 18 km from the moorings) in the instantaneous comparisons between the 1 sec TOPEX/POSEIDON sea level and the 5 min surface dynamic heights. The POSEIDON data have been merged with the TOPEX data by removing a 13.6 cm bias (Nerem et al., 1994) which can vary by several centimeters

(Ménard et al., 1994). The first 19 10-day cycles are considered here, covering the period from September 25, 1992 to March 30, 1993. For the purposes of evaluating the satellite versus the in situ sea level time series, the barotropic tides were removed from the altimeter data using the tidal corrections from several tide models that were at our disposal, i.e., enhanced modified Schwiderski (1980), Cartwright and Ray (1990), and Ray et al., (1994). The inverse barometer effect due to atmospheric pressure loading was accounted for using the GDR correction based on the ECMWF (European Center for Medium-Range Weather Forecasting) atmospheric surface pressure analysis and on sea level pressure observed during TOGA-COARE near the 2°S-156°E mooring.

3. Description of Major Observed Phenomena

3.1. *Regional low-frequency context*

The field phase of this study (August-September 1992 to February-March 1993) took place between the two major warming episodes in the eastern equatorial Pacific which characterized the 1991-93 El Niño (McPhaden, 1993). Figure 3, which represents the longest sea surface dynamic height measurement in the western Pacific, places our study into a more general context. In the western equatorial Pacific, the 1986-87 and 1991-94 El Niño were characterized by a drop of sea level of more than 20 dyn cm. The 1988-89 La Niña was also notable with a sea level rise which picked up in early 1989 by about 10 dyn cm. During boreal fall/winter and especially during the onset of El Niño, winds in the western Pacific were punctuated by frequent westerly wind bursts often associated with enhanced 40-60 day intraseasonal Madden and Julian (1971) wave activity (Kessler et al., 1995). These westerly wind bursts excited a series of eastward propagating low baroclinic mode equatorial oceanic Kelvin waves which were detected in both the TOGA-TAO time series (Kessler et al., 1995), and in the GEOSAT and TOPEX/POSEIDON altimeter data (Delcroix et al., 1994; Busalacchi et al., 1994). Recent work supports the idea that these waves may be important in the dynamics of El Niño (Kessler and McPhaden, 1995; Picaut and Delcroix, 1995).

To place our study in the context of regional scale variability occurring in the western equatorial Pacific during August 1992-March 1993, Figure 4 shows the surface wind and dynamic height time series between 8°N and 8°S, in the longitude range 156°E-165°E. Southeast tradewinds prevailed in the latter part of 1992 south of the equator, giving way to a monsoonal circulation in early 1993 with northeasterlies north of the equator and northwesterlies south of the equator (Figure 4a). Superimposed on this seasonal circulation were four episodes of intensified westerly winds within a few degrees of the equator. These episodes, each of which lasted 2-4 weeks, took place in September, October-November,

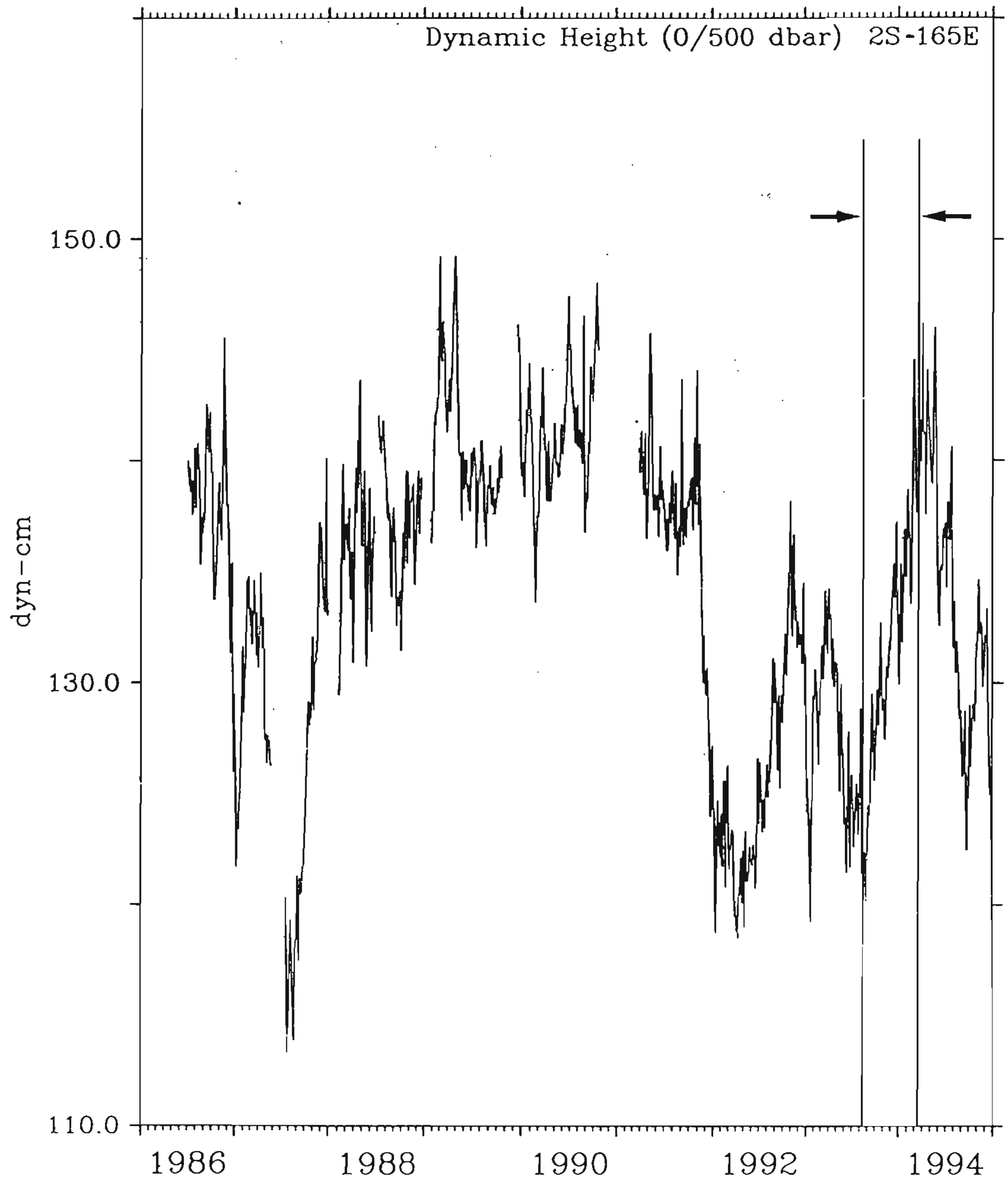


Figure 3. 5-day mean sea surface dynamic height time series (1986-94) relative to 500 dbar at 2°S-165°E calculated from the ATLAS thermistor chain and a mean T-S relation. The August 1992 - March 1993 period of the experiment is outlined within the two arrows.

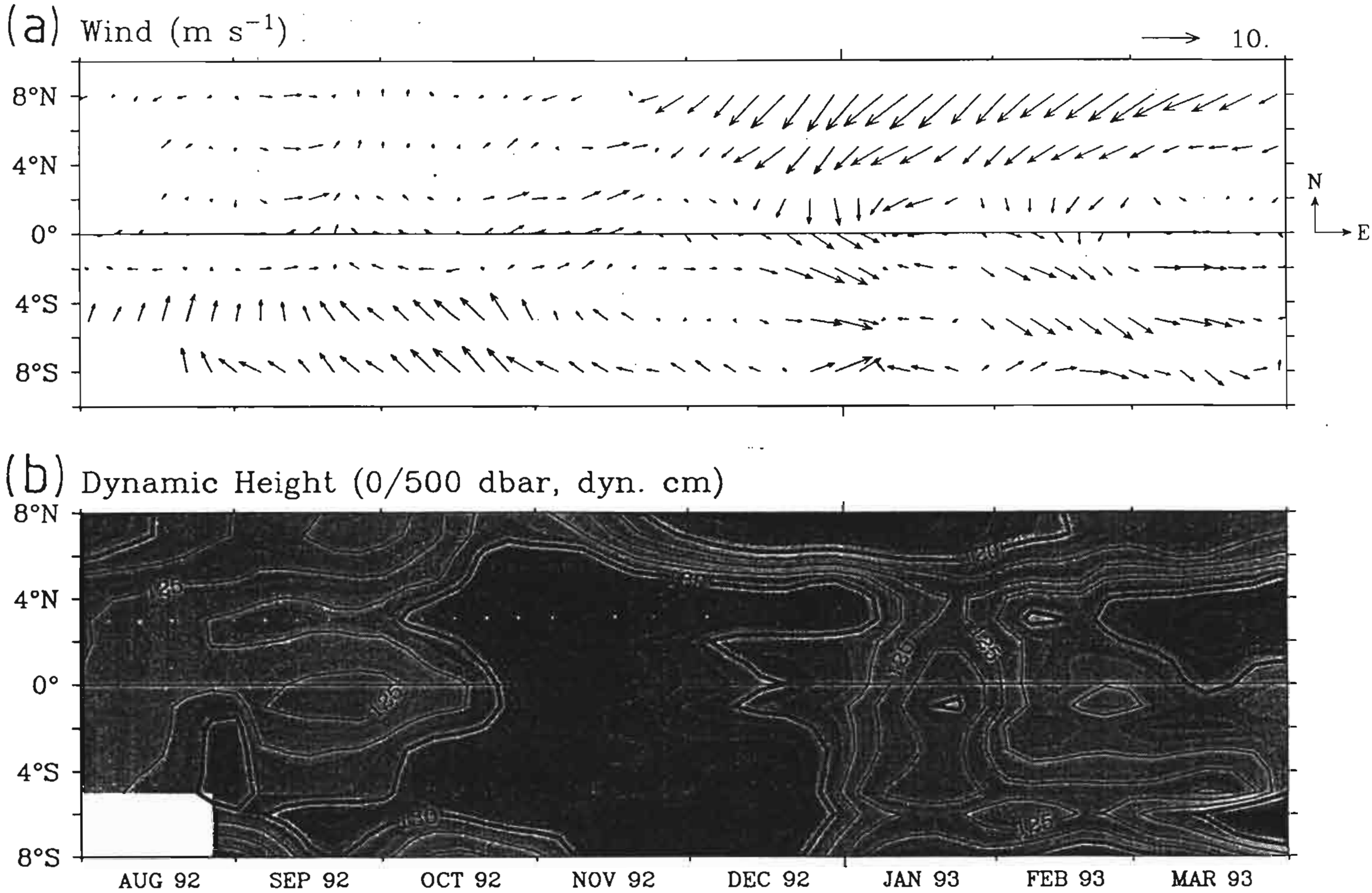


Figure 4. (a) 5-day mean surface wind and (b) surface dynamic height (0/500 dbar) around 160°E during the period of the experiment. The data came from the TOGA-TAO moorings within 8°N-8°S and averaged across 156°E and 165°E. Dynamic height is calculated from the thermistor chain and a mean T-S relation; contours are every 2.5 dyn cm.

December-January, and February-March. The strongest of these westerly episodes occurred in December-January, with 5-day mean wind speeds up to 5 m s^{-1}. The September-November events tended to be stronger north of the equator, whereas the December-March events were stronger south of the equator, reflecting in part the structure of the mean seasonal cycle on which they were superimposed.

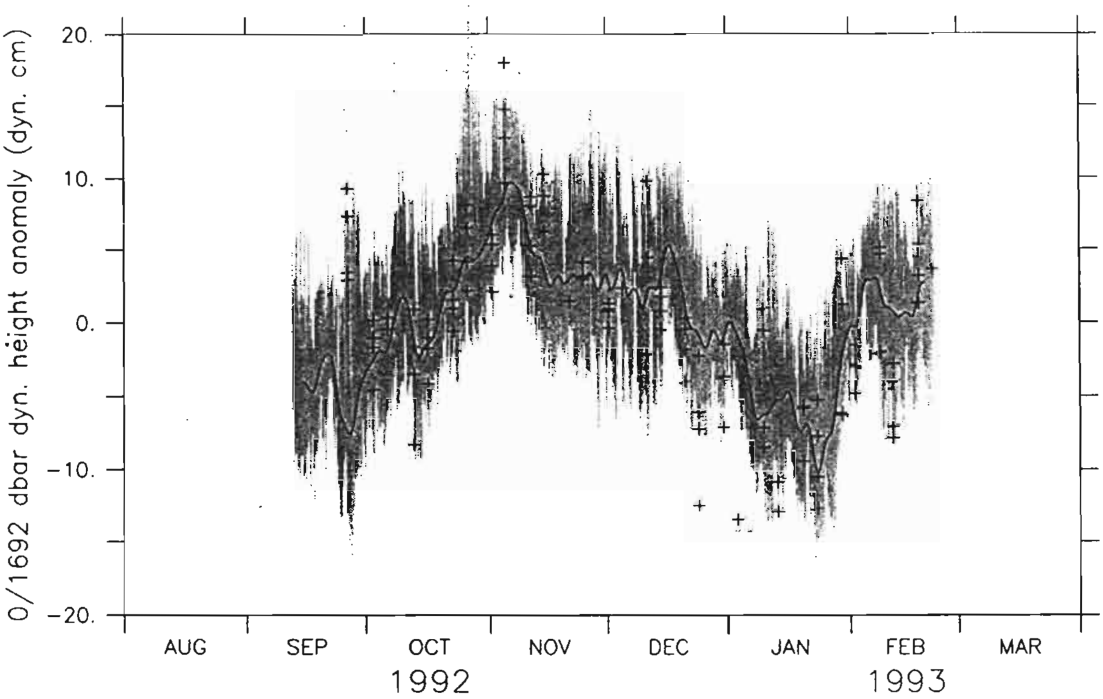
The regional sea level response to these westerly wind episodes varied from one episode to the next between 156°E and 165°E, most likely because of the different spatial structures (both latitudinal and longitudinal) of the wind forcing in relation to the mooring sites. Dynamic height, for example, rose 10 dyn cm within a few degrees of the equator in association with the October-November westerly wind burst (Figure 4b). This was followed in December-January by a rapid decrease of 10 dyn cm associated with a rise of the thermocline, in response to the sudden wind changes from westerly to easterly (Eldin et al., 1994). The September and February-March westerly wind episodes on the other hand had a much less pronounced impact on the surface dynamic height.

In addition to these intraseasonal dynamic height variations, there was also a large 15 dyn cm decrease in sea level near 8°N from November-January, which may have been associated with seasonal cooling during the boreal fall-winter. Seasonal dynamic height variations were not so evident in the southern hemisphere, perhaps because the seasonal cycle there was obscured by intraseasonal and/or interannual variations, the latter of which lead to a sea level lower than normal by 10-15 cm in the western Pacific throughout the period of our study.

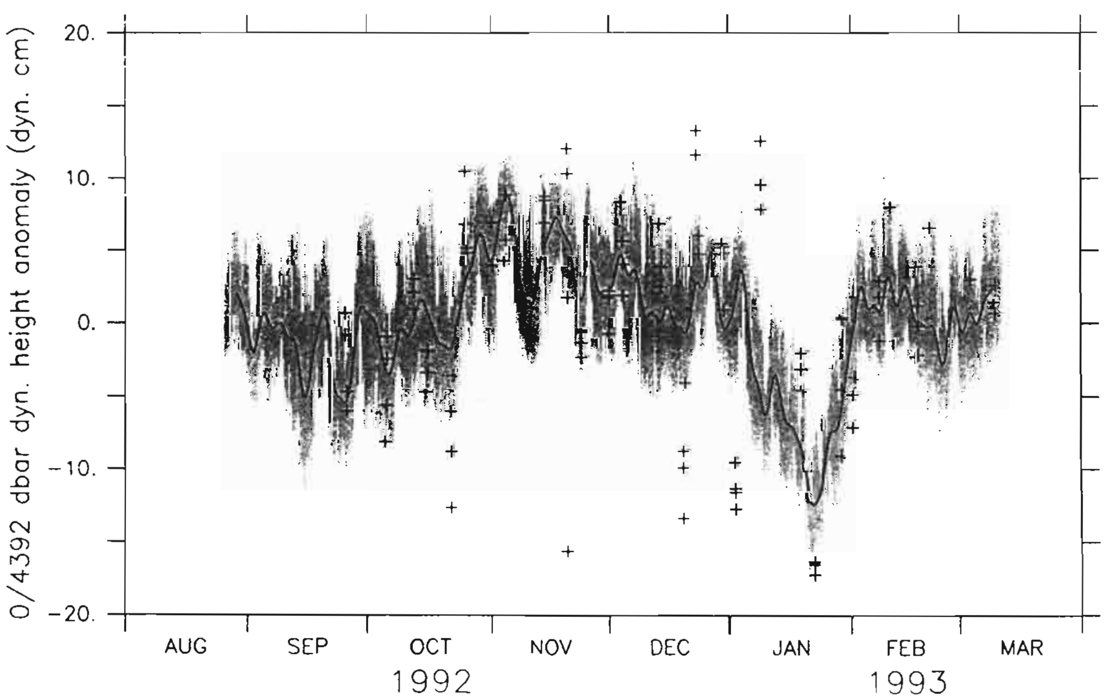
3.2. *Spectrum of variability at the validation sites*

Time series of dynamic height at the surface relative to the bottom calculated at 5 min intervals are presented in Figure 5. As can be seen, the dynamic height at both locations is a combination of high frequency and low frequency variations. The high frequency variability in surface dynamic height is distinctly greater at 2°S-156°E than at 2°S-164.4°E. It is also worth noting that the range of variation at this location encompasses most of the eight 1 sec TOPEX/POSEIDON sea level measurements nearest to the mooring sites. The implication for these high frequency fluctuations relative to the 10 day TOPEX/POSEIDON sampling will be discussed in sections 4 and 5.

Spectral analysis of the dynamic height series at different levels (Figure 6) reveals, in the high frequency band, the dominance of a strong semi-diurnal signal with surrounding energy around 4, 6 and 24 hours. These signals are dominant in the surface layer and remain

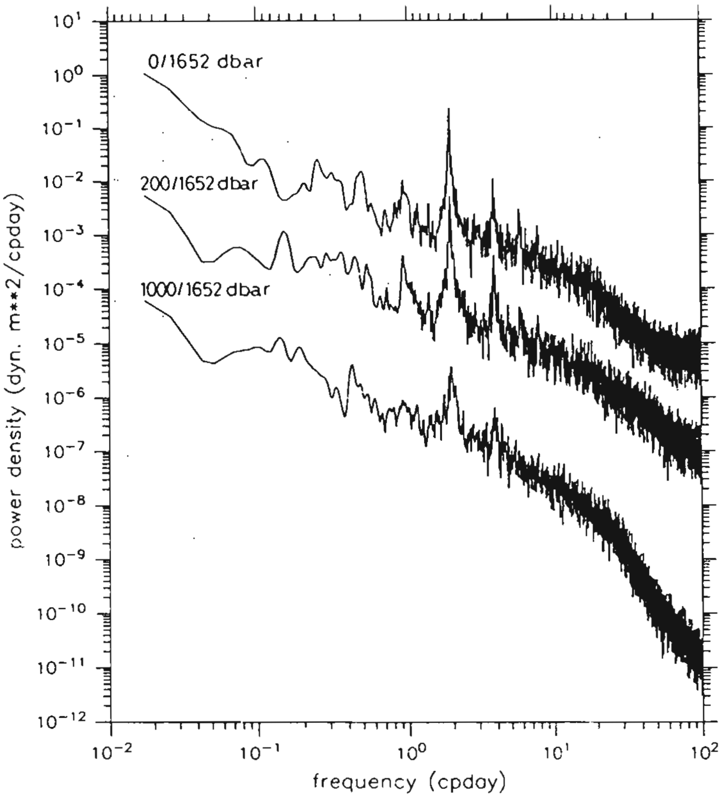


(a) 2°S - 156°E

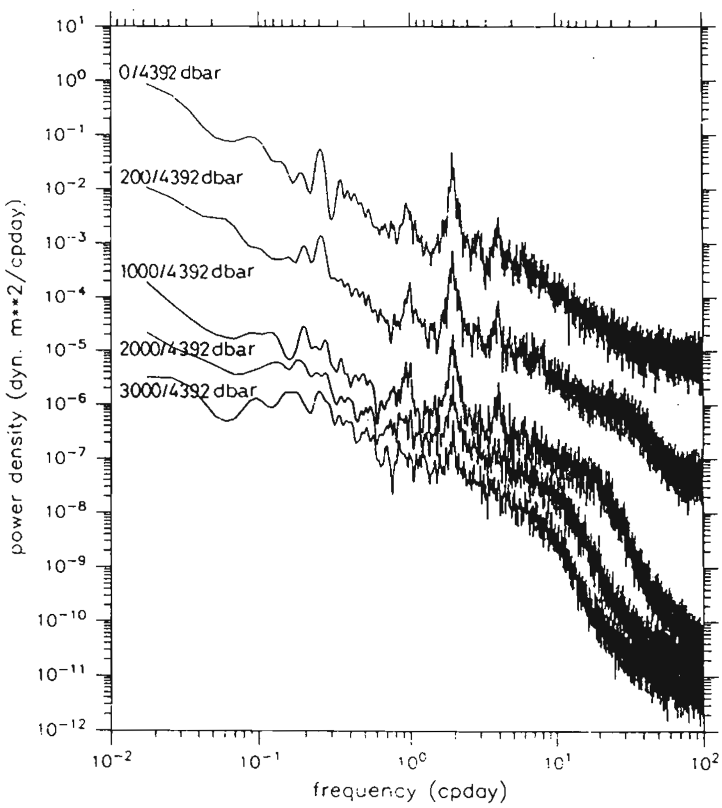


(b) 2°S - 164° E

Figure 5. Original 5 min surface dynamic height (light line) and its low pass filtered (5-day Hanning filter, heavy line) time series. Superimposed are the 1 sec sea level data of the 8 points of TOPEX/POSEIDON measurement (+) nearest to the mooring sites. All time series are anomalies relative to the period of measurements, (a) 2°S-156°E, (b) 2°S-164.4°E.



(a) 2°S-156°E



(b) 2°S-164°E

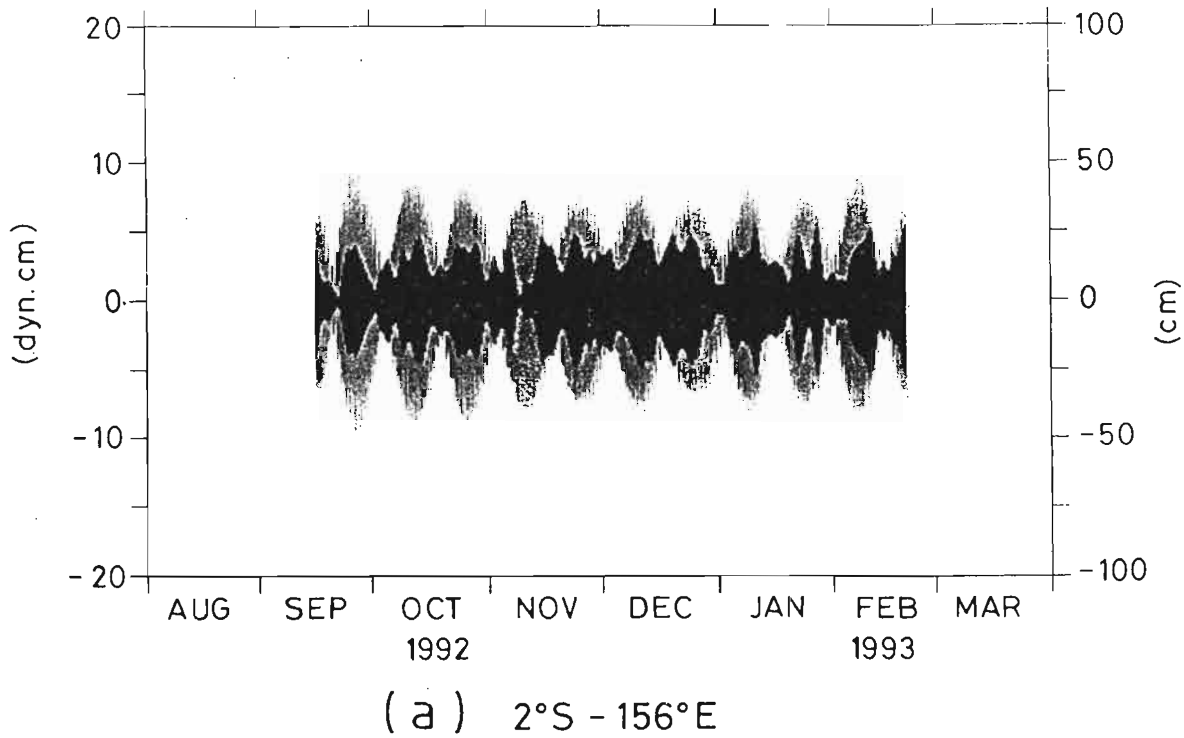
Figure 6. Spectrum of dynamic height time series relative to the bottom at different level, (a) 2°S-156°E and at level 0, 200 and 1000 dbar, (b) 2°S-164.4°E and at level 0, 200, 1000, 2000 and 3000 dbar. The spectra are shifted for clarity.

at depth. In the lower frequency band, there is some energy around 4 days, 10 days and longer periods. This spectral analysis suggests a separation between high and low frequency variability at around 2 days. Figure 5 illustrates the separation between low and high frequency variability in the surface dynamic height from the two moorings. Low frequency variability is similar with a standard deviation of 4.3 dyn cm at 2°S-156°E and 3.9 dyn cm at 2°S-164.4°E. As noted above, high frequency surface variability (period less than 2 days) is definitely of larger magnitude at the 2°S-156°E site with a standard deviation of 3.5 dyn cm compared to 2.7 dyn cm at 2°S-164.4°E.

3.3. *High-Frequency Variability at the validation sites*

Most of the high frequency variability seen in surface dynamic height is associated with internal tides with the M2 and S2 constituents being dominant. Complex demodulation analysis around 12.5 hours, indicates these dynamic height variations associated with the semi-diurnal internal tides are most energetic in the surface layer and confirms their presence all the way to the bottom (Figures 6, 7 and 8). They have larger amplitude at the shallow site (1739 m at 2°S-156°E) than on the abyssal plain (4400 m at 2°S-164.4°E) with standard deviation of respectively 2.3 and 1.4 dyn cm. Over the 6-7 months of our experiment, they appear as a superposition of wave trains of 5-15 day duration. Some similarities between the complex demodulation of the surface dynamic height and barotropic tides at the two sites suggests a possible relation between internal tides and spring tides in setting up these wave trains (Figure 7). This relation between baroclinic and barotropic tides is more obvious at the shallower 2°S-156°E site where the internal tides are stronger and apparently the barotropic tides are smaller (with only 21 days of BPR measurements at 2°S-156°E the modeled Schwiderski tides are used as a proxy for the observed tides). The temporal and spatial variability of these wave trains is examined in detail over a specific month (e.g., January 1993) through the representation of the original high frequency variability and its complex demodulation (Figure 8). Vertical coherence varies with time but both amplitude and duration are found to generally decrease with depth.

A detailed examination of the time series reveals that on some days, high energy solitary waves, related to the semi-diurnal internal tides, are clearly detectable at the shallower 2°S-156°E site (Figure 9). No such evidence is found on the abyssal plain at 2°S-164.4°E during the 6-month duration of the experiment. The strongest solitary waves exhibit variations that are coherent and in phase from surface to bottom. Within less than an hour, they can give rise to isopycnal displacements of up to 100 m below the pycnocline and to sea surface displacements of up to 30 dyn cm. Ship radar observations near the 2°S-156°E site during the COARE Intensive observation Period showed that they were probably coherent



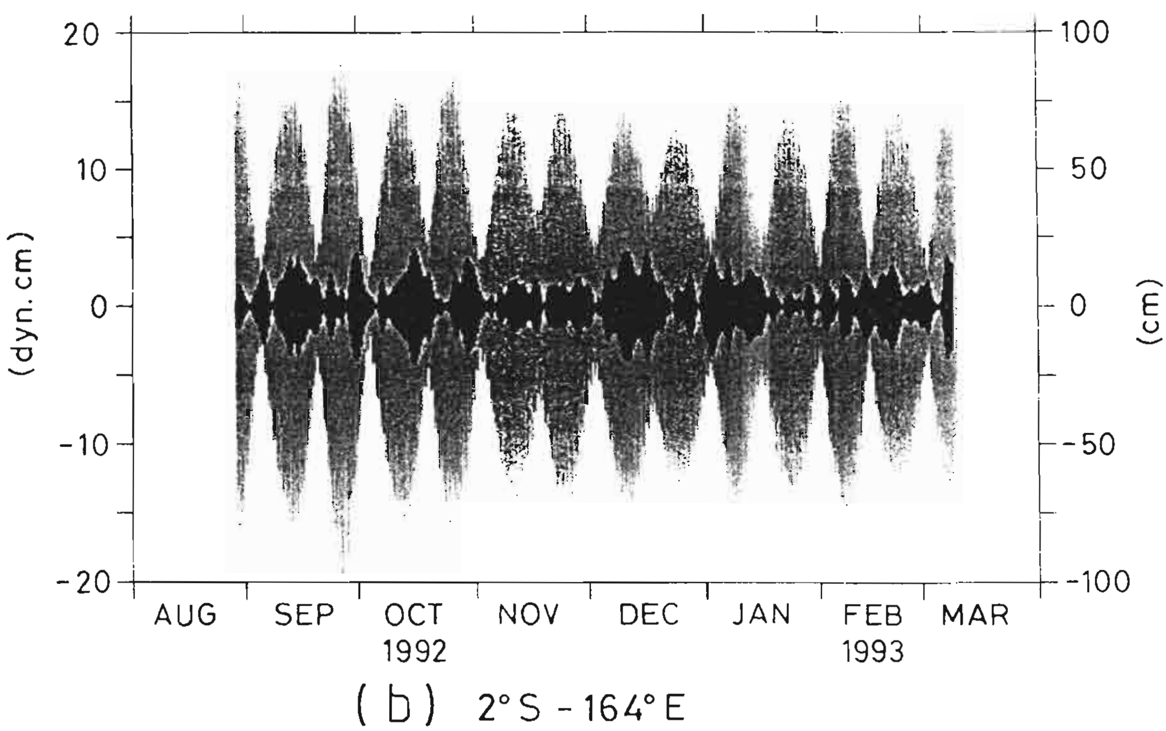


Figure 7. Complex demodulation (around 12.5 hours) of the sea surface relative to bottom dynamic height (heavy line) and of the barotropic tides (light line), (a) at 2°S-156°E using 13 constituents of the Schwiderski tide model, (b) at 2°S-164.4°E using the 59 constituents of the tides observed with the BPR. For convenience the baroclinic and barotropic tides are represented with a 1 to 5 ratio, i.e., within +/- 20 dyn cm (left axes) and within +/- 100 cm (right axes).

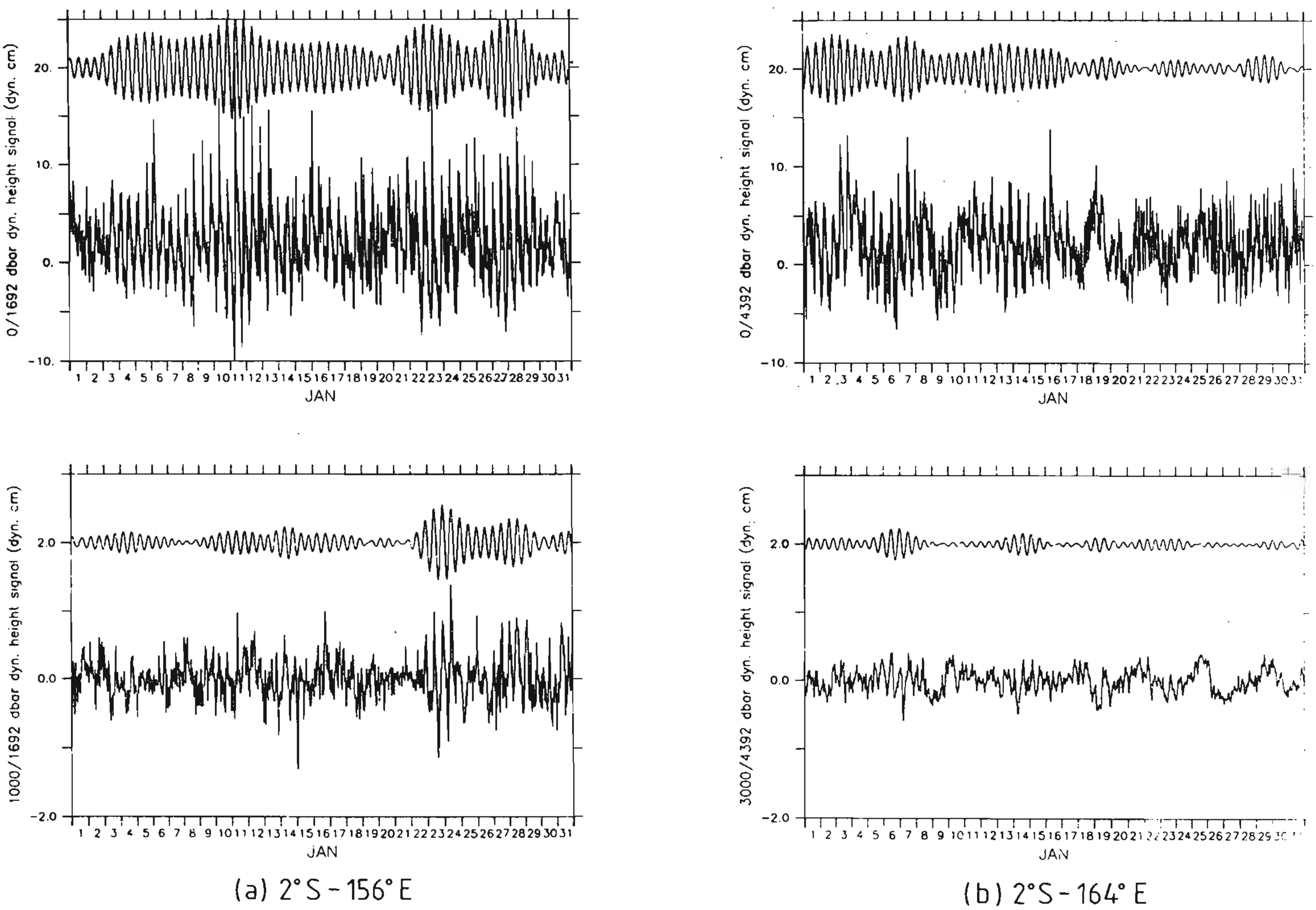


Figure 8. High pass filtered (5-day Hanning filter) and complex demodulation (around 12.5 hours) of the dynamic height series relative to the bottom in January 1993, (a) 2°S-156°E at the surface and 1000 dbar, (b) 2°S-164.4°E at the surface and 3000 dbar.

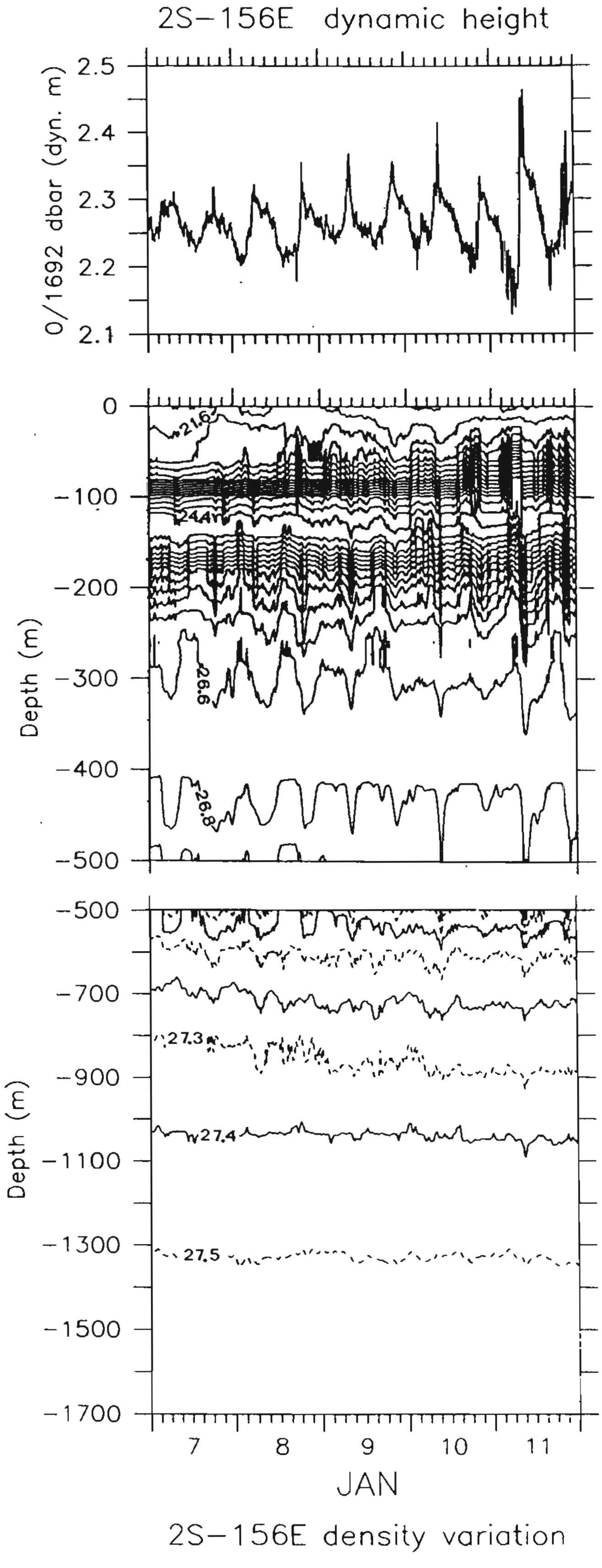


Figure 9. Example of strong solitons associated with the semi-diurnal tides at 2°S-156°E in January 7-11, 1993. Top panel: sea surface dynamic height relative to bottom, bottom panel: vertical density structure within 0-500 m and within 500 m and the bottom.

over 20-30 km along crest (R. Pinkel, personal communication, 1994). All these observations strongly suggest that the proximity of rough bottom topography may be a dominant factor in the generation of both the stronger internal tides and solitons at 2°S-156°E.

3.4. *Low-frequency variability at the validation sites*

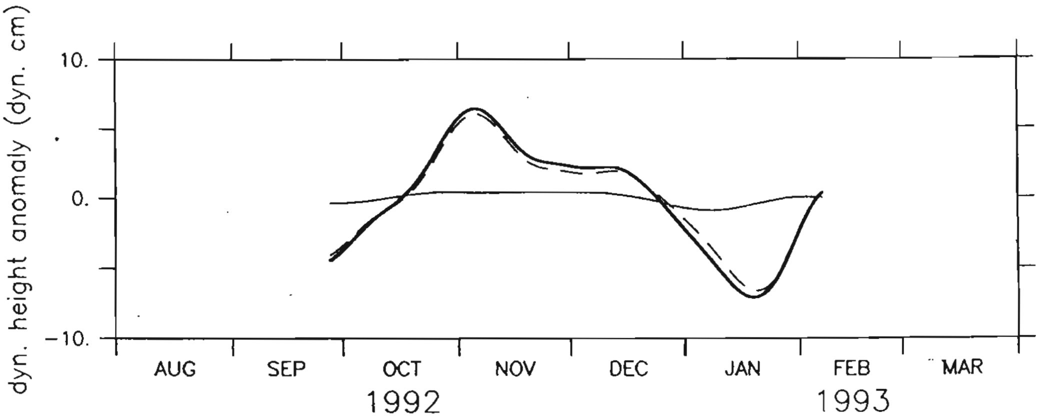
With the large space-scale of low-frequency equatorial phenomena (e.g., Meyers et al., 1991), the two validation sites exhibit very similar low-frequency surface to bottom dynamic height variability, especially on monthly time-scales observable by the 10-day repeat altimetric measurements (Figure 10). As noted in section 3.1., surface dynamic height is dominated by the successive sea level rise associated with the October-November westerly wind burst and the sea level fall associated with the January wind change from westerly to easterly. Most of this signal is dominated by variations in the upper 500 m. Specifically, the dynamic height standard deviation for 500 dbar relative to bottom is 0.6 and 0.7 dyn cm compared to 4.1 and 3.4 dyn cm for surface relative to bottom, respectively at 2°S-156°E and 2°S-164.4°E (Figure 10).

4. INTERCOMPARISON STUDY

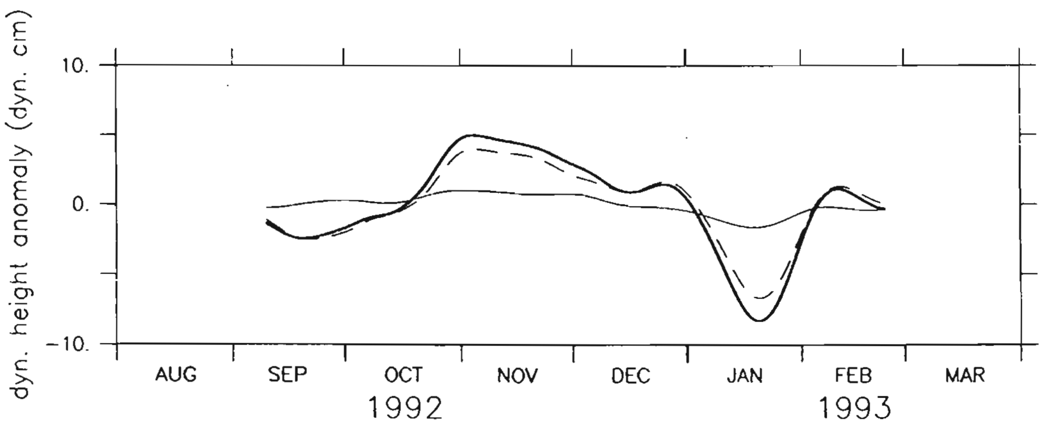
4.1. *Instantaneous comparison*

Given the general overlap of the 1 sec TOPEX/POSEIDON sea level retrievals and the 5 min surface dynamic height evidenced in Figure 5 (especially at 2°S-156°E), it is of interest to determine the level of error in the instantaneous comparison between the satellite and in situ sea level measurements. Even if the TOPEX/POSEIDON mission was designed mostly for large-scale studies, this exercise may be informative in terms of instantaneous corrections applied to the altimetric measurements (e.g., tidal and inverse barometer corrections).

The 1 sec TOPEX/POSEIDON sea level anomalies, at a given pass of the satellite over a mooring site, are compared with the corresponding in situ 5 min surface dynamic height anomalies. With the satellite flying over a site twice every 10-day cycle, a total of 27 passes were available during our experiment, of which 3 (6) passes were made by the POSEIDON altimeter at 2°S-156°E (2°S-164.4°E). We considered at first the 8 points of measurement closest to a site (i.e., within 18 km from a site). For a specific point, the TOPEX/POSEIDON anomaly is defined relative to the mean of all 1 sec measurements at this point available over the duration of the experiment (i. e., mean calculated over 14



(a) 2°S-156°E



(b) 2°S-164°E

Figure 10. Low frequency (30-day Hanning filter) dynamic height time series: surface to bottom (heavy line), surface/500 dbar (dashed line), 500 dbar/bottom (thin line), (a) 2°S-156°E, (b) 2°S-164.4°E.

descending or 13 ascending tracks). In the same way, the dynamic height anomaly is defined relative to the mean of the 5 min dynamic heights corresponding to the previous TOPEX/POSEIDON measurements. Since tides were measured from the BPR at 2°S-164.4°E and atmospheric sea level pressure measured close to 2°S-156°E, the tidal and atmospheric sea level pressure corrections applied to the TOPEX/POSEIDON dataset are considered separately.

With the enhanced GDR provided by the NASA/GSFC ocean altimetry group, three tidal corrections were included. They come from the enhanced modified Schwiderski (1980), Cartwright and Ray (1990) and Ray, Sanchez and Cartwright (1994) models. From these three models, 13, 5, and 4 tidal constituents were respectively available at 2°S-156°E and 2°S-164.4°E (courtesy of C. Le Provost). With 6 months of BPR measurements at 2°S-164.4°E, 59 tidal constituents were calculated ranging from M8 to Msm. The first thirteen constituents are listed in Table 2, and the comparisons between the BPR and the various tide models are summarized in Table 3. All three tide models used the long period equilibrium tides. These long periods contribute weakly to the total tidal signal with 1.5 cm standard deviation as compared to 46 cm standard deviation for the hourly BPR record. However, as discussed by Wunsch (1977) and Miller et al. (1993) in the tropical Pacific, these semi-monthly and monthly long period tides are not exactly in equilibrium, with a 0.6 cm rms difference from the equilibrium tides. Therefore, a BPR55 comparison (i.e., with Msm, Mm, Msf and Mf omitted) was added in Table 3 as an additional reference for the comparisons between the tide models and the BPR. The 7.6 cm rms difference between BPR13 and BPR05 compared to the 2.0 cm rms difference between BPR13 and BR59 indicates that 13 constituents is a significant improvement in reproducing the tides at 2°S-164.4°E. Using only 4 or 5 of the major constituents (common to the three tidal models), we note that the Schwiderski model fits best the BPR (Table 3). This is probably due to its ability to reproduce better the observed S2 constituent, as all three models result in an identical rms difference with the BPR when the S2 constituent is moreover omitted from the comparisons. The radiational component of the S2 constituent, measured with the BPR, is partly included in the Schwiderski model, as this model is the only one forced by tide gauge measurements. Keeping in mind that the Schwiderski model is the best to fit our BPR measurements with 4 constituents, we note that in its enhanced modified 13 constituents version, the rms difference with BPR13 is 4.1 cm.

Spectral analysis of the sea level atmospheric pressure observed near the 2°S-156°E site, clearly shows a strong semi-diurnal signal, a diurnal signal and some energy in the 4-7 day and 30-60 day band (the last corresponding to the Madden-Julian oscillation). The semi-diurnal and diurnal signals correspond to the atmospheric tides of thermal origin (Chapman

TABLE 2. Period (hours), amplitude (cm) and phase (°) of the major tidal constituents at 2°S-164.4°E, issued from the bottom pressure recorder (BPR) and the Schwiderski (Schw), Cartwright-Ray (CR) and Ray-Sanchez-Cartwright (RSC) models.

		BPR		Schw		CR		RSC	
Const	Period	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase
M2	12.42	52.2	146	47.8	144	52.2	141	54.1	141
S2	12.00	28.5	160	27.4	159	27.0	150	30.9	153
K1	24.00	15.4	62	15.0	61	15.2	54	15.3	58
N2	12.66	10.8	146	9.0	145	10.7	144		
O1	25.82	9.2	41	8.6	40	9.2	35	8.5	42
K2	11.97	8.5	154	7.3	155				
P1	24.07	4.8	60	4.9	61				
L2	12.19	2.1	138	1.4	148				
μ2	12.87	2.0	136	1.5	151				
T2	12.02	1.9	157	1.5	153				
ν2	12.22	1.9	146	1.7	145				
Q1	26.87	1.6	22	1.6	20				
2N2	12.63	1.6	136	1.3	152				

TABLE 3. rms difference (cm) between the predicted tides calculated with N constituents derived from the BPR and the three tidal models.

BPR/BPR					BPR/Schw				BPR/CR			BPR/RSC	
N	55	13	5	4	N	13	5	4	N	5	4	N	4
59	1.5	2.0	7.9	11.1	59				59			59	
55		1.3	7.7	11.0	55				55			55	
13			7.6	11.0	13	4.1			13			13	
5				7.7	5		3.9		5	5.3		5	
4					4			3.6	4		5.3	4	4.7

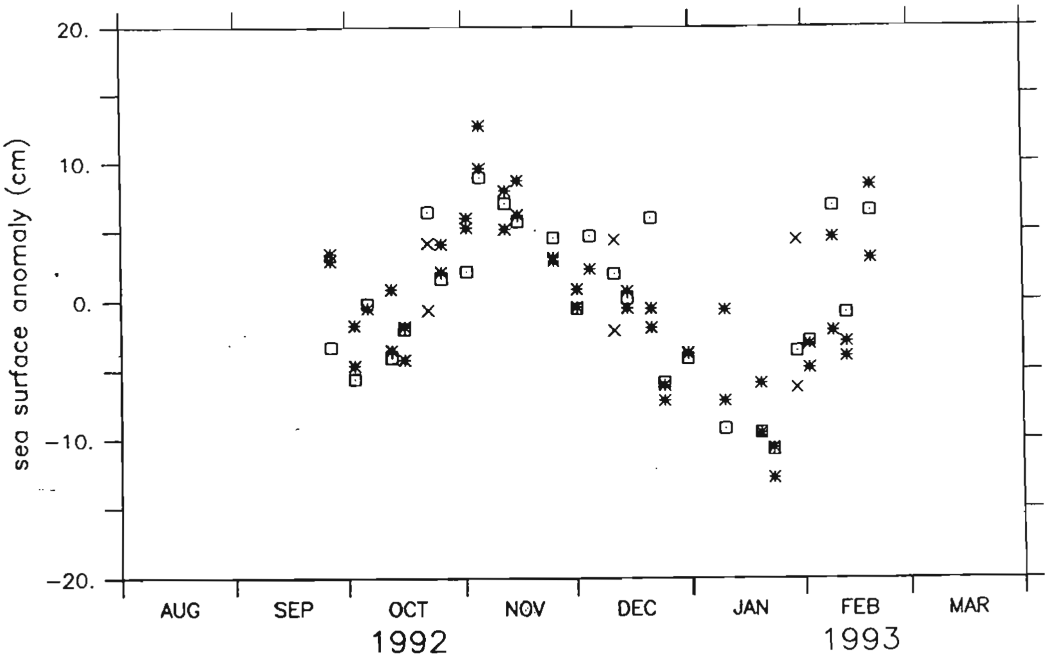
and Lindzen, 1970). They are clearly evident within the tropics where atmospheric pressure is usually stable. Given the 6-hour window of data assimilation in the ECMWF model, they are probably poorly resolved in this model. In any case the inverted barometer correction applied to the altimetric measurements is not reliable for periods shorter than 2 days (Ponte et al., 1991).

The instantaneous comparisons were done between the TOPEX/POSEIDON sea level anomalies and the sea surface dynamic height anomalies, using the corrections issued from the three different tidal models (Table 4). Using the 8 nearest points to the mooring sites, the rms differences are around 5-6 cm for all models. The rms differences decrease significantly if only the 4 nearest points of measurement are considered (i.e., 2 points of measurement along the descending and 2 points along the ascending tracks), especially using the Schwiderski tide model. Given the reduced number of POSEIDON measurements (3, 6 as compared to 24, 22 TOPEX measurements, respectively at the 2°S-156°E and 2°S-164.4°E mooring sites), the adjustment (within a few cm) of the POSEIDON bias does not ameliorate the preceding results. However, the instantaneous comparisons improve a little if the POSEIDON information is removed, reducing the rms differences to 3.3 cm at 2°S-156°E and 3.7 cm at 2°S-164.4°E. The replacement of the tidal corrections included in the TOPEX/POSEIDON GDR by the observed tides (predicted from the constituents calculated from the BPR measurements at 2°S-164.4°E) does not improve all the previous results, even if all the 59 BPR constituents are used (Msm to M8). In that case, we are assembling 1 sec TOPEX/POSEIDON sea level with tidal corrections which cannot resolve periods shorter than 3.1 hours (M8), and at this point we probably have reached the level of instantaneous error in tidal observations and models.

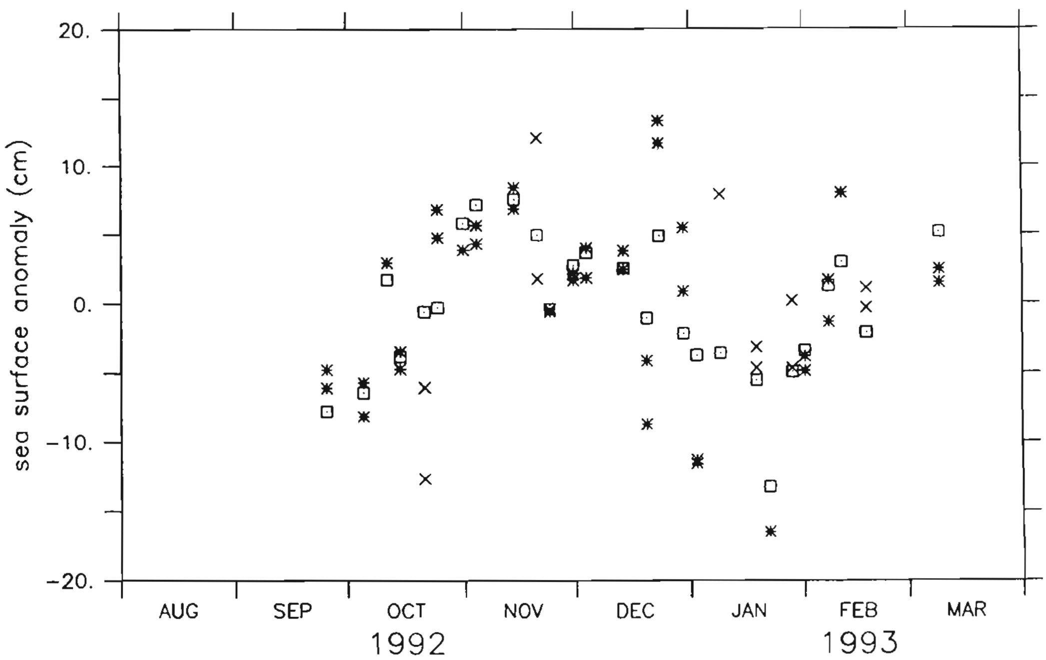
Figure 11 depicts the comparison with the nearest 4 points of TOPEX and POSEIDON measurements. At 2°S-164.4°E the dispersion in POSEIDON measurements is evident, suggesting noisier measurements than with the TOPEX altimeter. The spectral characteristics of TOPEX and POSEIDON agree well at low wavenumbers, however, they differ at short wavelengths, POSEIDON spectra being more energetic. This is essentially due to the TOPEX tracker characteristics and to the way the acceleration correction is made on the GDR (P. Vincent, personal communication, 1995). Nevertheless, the dispersion of TOPEX measurements is also notable in December-January. During this period the winds were strong and varied in direction (Figure 4), and it is possible that the sea state correction, of significant amplitude (Figure 12), was not adequate. Note that this last figure is also characterized by a greater sea state correction with POSEIDON than with TOPEX (Gaspar et al., 1994). This correction is a function of the wind speed and of the significant wave height. Despite the 10-day sampling, the altimetric winds seem to be in good accordance with the

TABLE 4. rms difference (cm) between the 1 sec TOPEX and POSEIDON sea level and the 5 min dynamic height, using the 8 and 4 sea level points nearest to the mooring site and the three tidal models.

	2°S-156°E	2°S-164.4°E
8 pts, all models	5-6	5-6
4 pts, RSC	4.6	4.6
4pts, CR	4.2	4.1
4pts, Schw	3.6	4.4
4 pts, Schw, no POSEIDON	3.3	3.7



(a) 2°S - 156°E



(b) 2°S - 164°E

Figure 11. Instantaneous comparison between the 5 min sea surface dynamic height (square) and the TOPEX (star) and POSEIDON (cross) sea level at the 4 nearest points to the mooring sites, (a) 2°S-156°E, (b) 2°S-164.4°E.

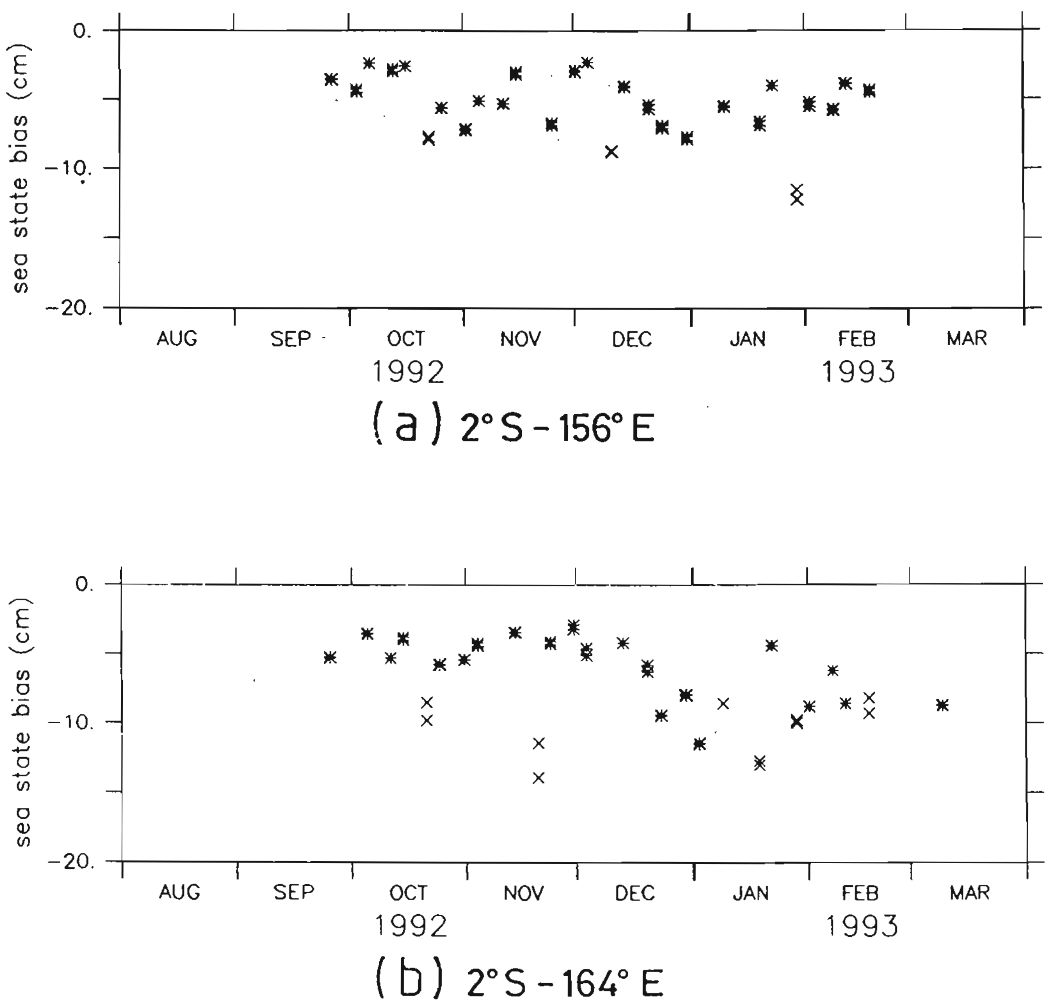


Figure 12. Sea state correction from the TOPEX (star) and POSEIDON (cross) altimeters, (a) 2°S-156°E, (b) 2°S-164.4°E.

winds observed from the two ATLAS moorings (not shown), and it is probable that the correction associated with surface waves was not accurately determined from the altimeters in a sea exposed to varying winds.

The inverse barometer hypothesis was tested in two ways. Following the result of Fu and Pihos (1994) in the western tropical Pacific, a -0.4 cm/mbar correction factor instead of the traditional -1 cm/mbar factor was applied to the inverse ECMWF barometer correction included in the TOPEX/POSEIDON GDR. At 2°S-156°E, the rms difference between the instantaneous comparison of the sea surface dynamic height and the altimeter sea level improves from 3.6 cm to 3.4 cm. Using the observed sea level atmospheric pressure near the 2°S-156°E mooring instead of the ECMWF pressure and the same -0.4 cm/mbar factor does not significantly change the preceding result with an rms difference of 3.3 cm. Essentially the same results were also obtained when we used the -1 cm/mbar correction. This confirms the weakness of the correction associated with the sea level atmospheric pressure in the tropics.

In summary, our instantaneous comparison between TOPEX/POSEIDON sea level and sea surface dynamic height at the two mooring sites results in a rms difference of 3-4 cm. This is surprisingly good knowing the numerous errors involved in such an instantaneous comparison. For example, we are comparing 5 min sea surface dynamic height with 1 sec TOPEX/POSEIDON sea level, barotropic tidal models are in error by 3-5 cm rms (Le Provost et al., 1995), the sea state correction is likely to be inadequate part of the time, and the inverse barometer correction should not be applied for periods shorter than 2 days (Ponte et al., 1991).

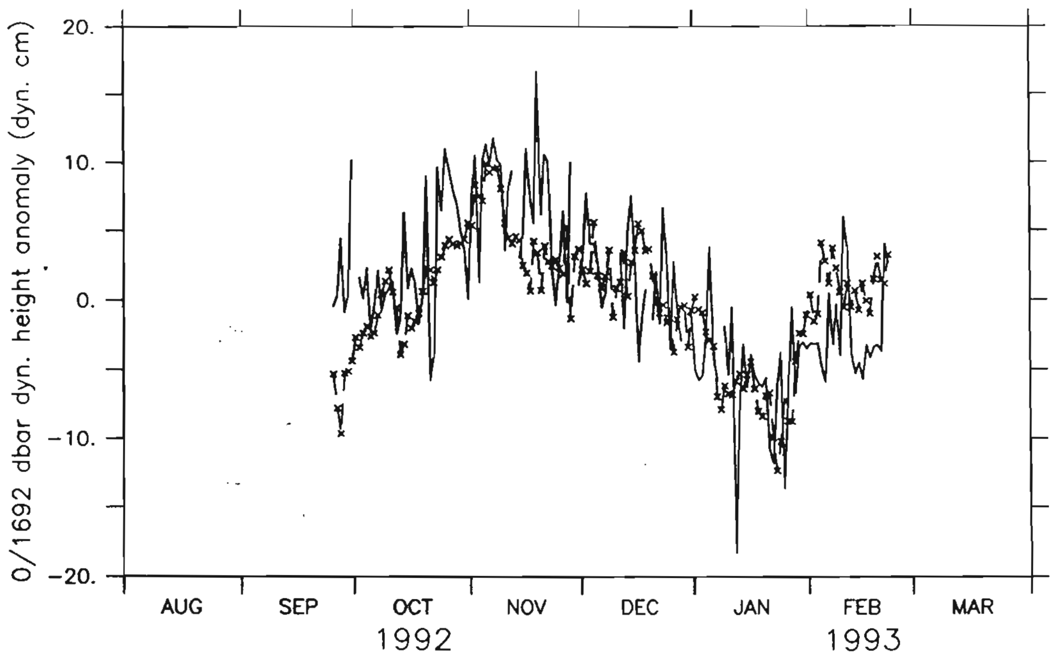
4.2. *Low-Frequency comparison*

Despite the encouraging results of the previous section, with extreme sea surface dynamic height variation of up to 30 cm on time scales as short as one hour, it is obvious that sampling error could be important given the 10-day repeat coverage of TOPEX/POSEIDON. Hence, we are interested in the extent to which the low frequency dynamic height variability (Figure 10) can be accounted for with appropriate space-time averaging of the altimeter data.

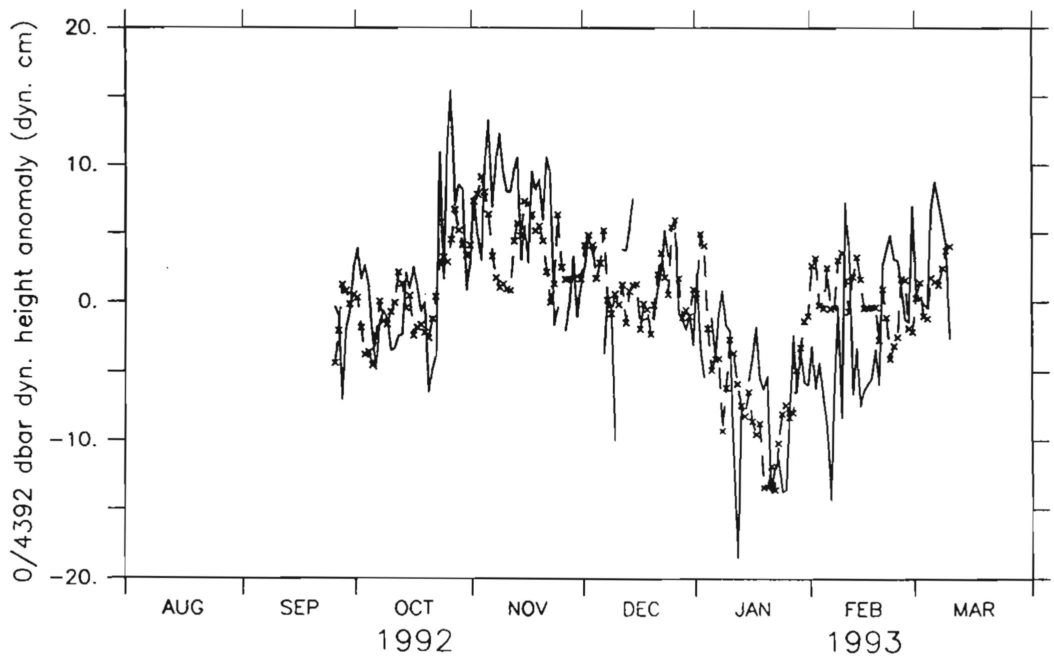
To perform the low frequency comparison, dynamic height data were averaged to produce daily means at both locations. Similarly, all TOPEX/POSEIDON data falling within a x degree longitude by y degree latitude box, centered on the mooring location, were averaged or interpolated into daily values, as the amount of spatial coverage varied according to the size of the box. A rectangle 20° longitude by 10° latitude was the minimum size resulting in nearly continuous daily series (94% of the days of the studied period have valid TOPEX/POSEIDON data). The percentage fell to 66%, 45% and 35% respectively for the 15° x 3°, 10° x 3 ° and 5° x 2° box, and the data were linearly interpolated to daily values. As an example, Figure 13 displays the daily time series of the surface dynamic height and TOPEX/POSEIDON sea level measurements falling in the 20° longitude by 10° latitude box. This figure clearly shows the need of low-pass filtering for both series, and especially for the TOPEX/POSEIDON sea level. With the 10-day repeat orbit, one would not expect to study phenomenon with period lower than the Nyquist 20-day period. In addition the main objective of the TOPEX/POSEIDON mission is to determine geostrophic surface current, and in the equatorial region geostrophy applies at least on the monthly time scale (Picaut et al., 1989). Therefore we have chosen a 30-day Hanning filter for the low-frequency comparison of the TOPEX/POSEIDON and surface dynamic height.

The TOPEX/POSEIDON data were also processed using 2-Dimensional (x-y) and 3-Dimensional (x-y-t) optimal interpolation techniques. The results for the 3-D optimal interpolation are presented in Figure 14. The decorrelation scales were chosen in space following Meyers et al. (1991) with 15° longitude and 3° latitude, and in time from the autocorrelation of the surface dynamic height time series at the two sites (25 days). We have tried to improve the low-frequency comparison by introducing a 2.6 m s^{-1} eastward phase propagation into the 3-D optimal interpolation scheme, assuming that the largest sea level variations at the mooring sites were associated with equatorial Kelvin wave propagation (section 3). As can be seen in Table 5, this technique only slightly improved the low-frequency comparison. Following the technique used in Picaut et al. (1990) for the determination of surface geostrophic currents at the equator from GEOSAT data, a combination of linear (Hanning) and non-linear (median) filters was also used along each individual track in order to reduce possible remaining noise or spikes along the track (400 km filter length). Such filtering had a negligible impact on the comparison, consistent with the reduction in alongtrack noise in TOPEX/POSEIDON data compared to GEOSAT data.

Our ability to determine the appropriate technique is impacted by the relatively short duration of the times series, and it is not clear that the low-frequency comparison benefits from these additional techniques (2-D, 3-D, 3D with propagation) beyond the comparison from the straightforward binning utilized at first (Table 5). Overall, the low-frequency comparison results in a very good correspondence between the TOPEX/POSEIDON sea level anomalies and the sea surface dynamic height anomalies with correlation of 0.93-0.96 and rms difference of 1.6-2.0 cm. This result is particularly good considering the low-frequency barotropic signal could not be determined from our observations.

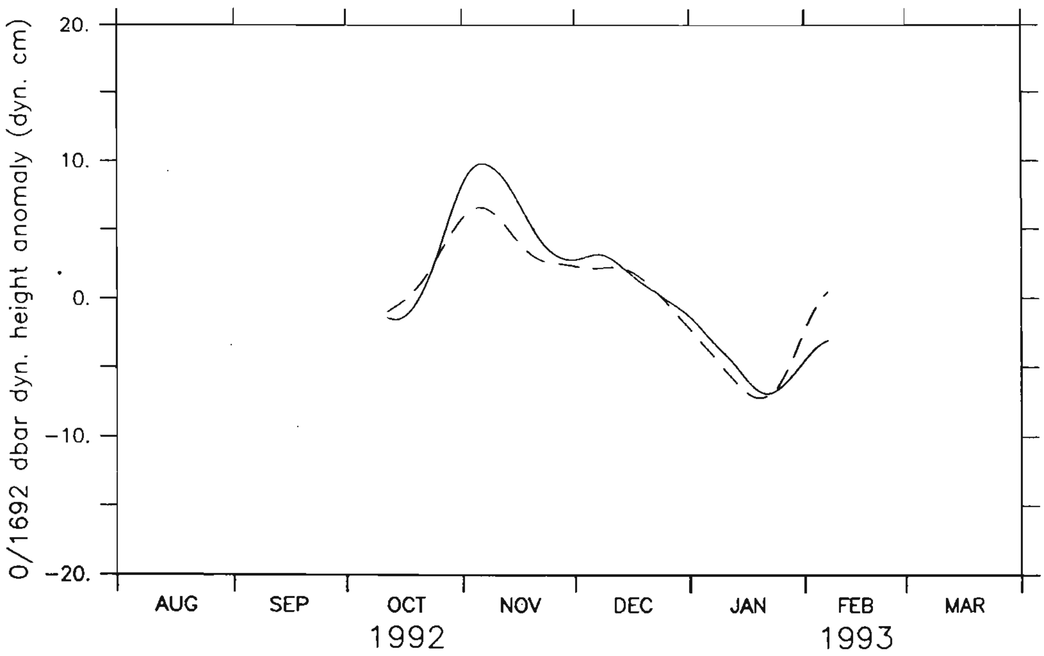


(a) 2°S - 156°E

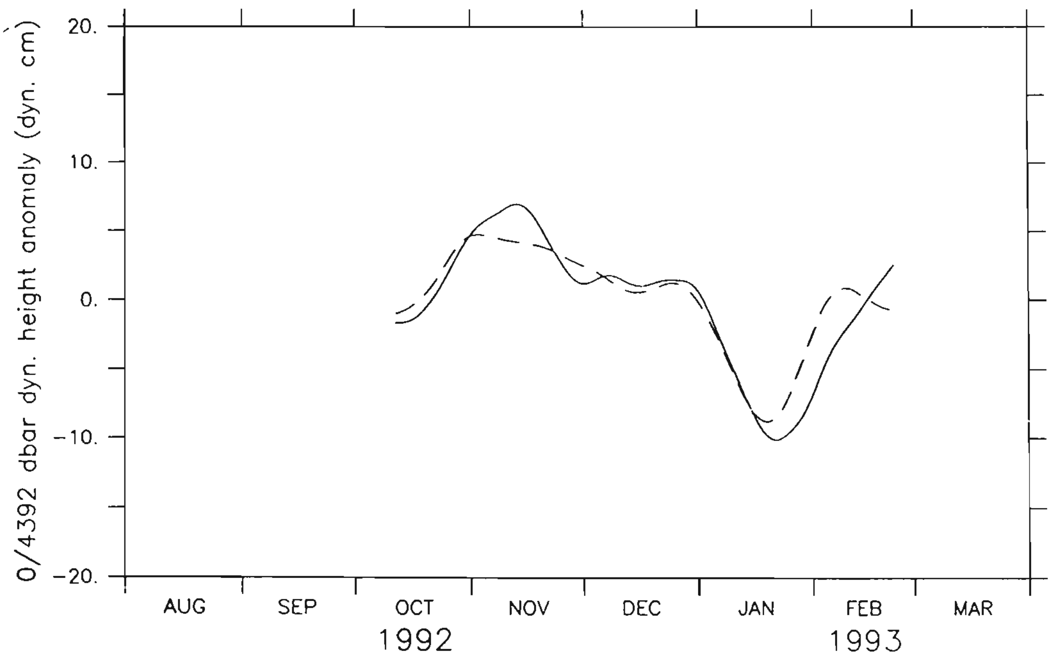


(b) 2°S-164°E

Figure 13. Comparison between the daily mean sea surface dynamic height (crosses) and the daily binned TOPEX/POSEIDON (full line) sea level within a 20° longitude x 10° latitude box, (a) 2°S-156°E, (b) 2°S-164.4°E.



(a) 2°S - 156°E



(b) 2° S - 164° E

Figure 14. Low frequency (30-day Hanning filter) comparison between the sea surface dynamic height (dashed line) relative to bottom and the TOPEX/POSEIDON sea level from the 3-D OI (full line), (a) 2°S-156°E, (b) 2°S-164.4°E.

TABLE 5. Correlation and rms difference (cm) between low frequency sea surface dynamic height and TOPEX/POSEIDON sea level anomalies using different space/time interpolation schemes (binning over x° longitude by y° latitude; optimal interpolation: 2-D, 3-D, 3-D with propagation).

		20x10	10x3	5x2	2-D	3-D	3-D prop.
2°S-156°E	Correl.	0.96	0.96	0.97	0.96	0.96	0.96
	rms dif.	1.7	1.8	2.2	2.0	1.8	1.6
2°S-164.4°E	Correl.	0.89	0.95	0.97	0.94	0.94	0.93
	rms dif.	2.2	1.5	1.3	1.6	1.9	1.8

5. Discussion and Conclusions

In the foregoing sections, we have presented a comparison of TOPEX and POSEIDON altimeter data and in situ time series data from two heavily instrumented ATLAS moorings of the TOGA-TAO Array in the western equatorial Pacific. The analysis was performed during the TOPEX/POSEIDON verification phase, spanning a 6-7 month period following the launch of the satellite. The period of our study also overlapped in time with the TOGA-COARE Intensive Observation Period (November 1992 - February 1993), providing a valuable regional scale observational framework in which to interpret the variations observed in both the satellite and moored time series data.

For the purpose of TOPEX/POSEIDON validation, standard instrumentation on the two ATLAS moorings was augmented with temperature sensors over the full depth of the water column, and in the upper 750 m with conductivity sensors (to estimate salinity) and pressure sensors. From these data, surface dynamic heights relative to the bottom were computed with a temporal resolution of 5 minutes. We estimated the accuracy of our surface dynamic height calculation at 2°S-156°E to be roughly 1 dyn cm. The accuracy at 2°S-164.4°E is probably closer to 1.5 dyn cm because of the coarser vertical resolution of subsurface temperature and salinity, because of the imprecise determination of the vertical displacements of the sensors below 750 m, and because the range of depths over which density was integrated to provide dynamic height estimates was greater there. Bottom pressure gauges were also deployed near the two ATLAS moorings to estimate the barotropic component of sea level. One of these instruments failed after 21 days (at 2°S-156°E) and both were affected by a low frequency drift. Hence, use of these data was confined to analysis of the tides, which at the diurnal and semi-diurnal frequencies are the most energetic components of barotropic sea level variability.

Both "instantaneous" and "low frequency" comparisons were performed using the anomalies of in situ dynamic height estimates and of satellite altimeter data. Instantaneous comparisons were intended to assess the accuracy of the altimeters and of the various corrections, whereas the low frequency comparisons were done to assess the potential reduction of sampling errors (primarily due to tidal aliasing) by temporally and spatially averaging. For the "instantaneous" comparisons, a number of TOPEX/POSEIDON 1 sec data points around the mooring sites were compared to the closest 5 min surface dynamic height estimates from the moorings. For the low frequency comparisons, we combined altimeter data around each validation sites, either with a simple binning technique or with an optimal interpolation technique, then low pass filtered the time series with a 30-day Hanning filter length.

Instantaneous comparisons, based on in situ dynamic height measurements and on altimeter retrievals corrected using the Schwiderski tidal model and ECMWF surface air pressure analyses to account for the inverted barometer effect, indicate rms differences of 3.6 cm at 2°S-156°E and 4.4 cm at 2°S-164.4°E. Note that these rms differences are reduced by 0.5 cm when POSEIDON data are omitted. With a 1-1.5 cm error in the dynamic height calculation at the mooring validation sites, these results suggest an altimeter measurement error of 3-4 cm at the two locations. The actual error may be even smaller because our comparisons are not truly instantaneous, since the satellite and in situ measurements may be separated by up to 5 minutes in time and 6 km in space. Moreover, we have not been able to estimate low frequency barotropic sea level variations from the BPR data because of sensor drift. This component of sea level variation, to the extent that it may be significant, is likewise included in the in situ/satellite differences.

The accuracy of the TOPEX/POSEIDON altimeter sea level measurements is sensitive to the choice of tidal correction scheme. Indeed, our low-frequency comparisons have been based on the tidal model correction (Schwiderski) that give, on a mean, the smallest rms instantaneous differences between the in situ and satellite measurements. For the three tidal models tested in this study, the rms differences ranged from 3.6 cm to 4.6 cm at 2°S-156°E, and from 4.1 cm to 4.6 cm at 2°S-164.4°E. We suspect, however, that the relative improvement in satellite sea level estimates based on different tidal models has a regional and temporal dependence. For example, Busalacchi et al. (1994) noted considerable improvement in the eastern equatorial Pacific using the tidal corrections of Ray et al. (1994). Thus, the results of our study should not be generalized to imply that the Schwiderski model is best for the purpose of correcting TOPEX/POSEIDON altimeter retrievals on a global basis at all times.

The rms difference between in situ dynamic height and instantaneous altimeter sea level decreased from 3.6 cm to 3.3 cm when substituting moored surface air pressure measurements for the ECMWF analyses at 2°S-156°E. From this small difference we would conclude that at least at this location, the ECMWF surface pressure analysis provided a satisfactory correction for the inverted barometer effect. However, the air pressure variations were not particularly strong at the validation mooring sites, with an observed 1.6 mbar standard deviation near 2°S-156°E. As with our conclusion regarding tidal models, it would be inappropriate to generalize about the suitability of the ECMWF pressure analyses to other times and other parts of the world ocean where air pressure variations may be much stronger than observed during the 6 months of our study, where the data density going into the

ECMWF analysis scheme may vary, and where the ocean's response may be dynamically different.

One of the more striking phenomena detected in our dynamic height time series was the quasi-permanence of semi-diurnal internal tides, with an rms amplitude of 2.3 cm at 2°S-156°E and 1.4 cm at 2°S-164.4°E. It is commonly believed that internal tides are generated by scattering of the barotropic tides in regions of irregular bottom topography (e.g., Hendershott, 1981; Morozov, 1995). Thus, the higher internal tidal amplitudes at 2°S-156°E are probably induced by the Ontong Java Plateau where the mooring was anchored in the proximity of rough topography with reefs, islands and trenches. In contrast, the 2°S-164.4°E mooring was deployed in the Nauru Basin, an abyssal plain characterized by much smoother bottom topography, farther from potential source regions than the 2°S-156°E site.

Associated with the internal tides at 2°S-156°E, there were episodes of large amplitude (up to 30 dyn cm) dynamic height increases which occurred abruptly within the span of one hour. These episodes generally occurred once per semi-diurnal tidal cycle and were usually clustered in groups extending over several days. It is likely that these large dynamic height changes at 2°S-156°E were a manifestation of solitary waves, generated in tandem with the internal tides in the region of rough bottom topography to the west and southwest of the mooring site. Similar abrupt dynamic height variations did not occur at 2°S-164.4°E over the abyssal plain, consistent with the hypothesis of generation by topographic scattering of barotropic tides.

Our observations suggest that the phase of the internal tides varied randomly relative to the barotropic tides, though their amplitude seemed sporadically related to the spring tides. Internal tides, and dynamically related solitary waves in regions of rough topography, are very difficult to predict. Therefore they are a source of sampling error in the determination of lower frequency variations from altimeter records. For low baroclinic mode motions, one expects the horizontal scale (1/4 wavelength) of internal tides to be about 20-30 km. Solitary waves observed near 2°S-156°E during COARE were coherent over similar distances along crest. For the instantaneous comparisons, best results (rms difference = 3-4 cm) were obtained by choosing only the 4 closest points in time and space to each 5 min dynamic height, i.e., within a maximum of 7 km from the mooring sites. This suggests that internal tides and solitons were seen, simultaneously in surface dynamic height and altimeter measurements, with similar amplitudes. Thus, it should be possible to reduce the signature of the internal tides and other sources of short time and space scale geophysical noise in altimeter analyses by implementing suitable space/time averaging schemes. Our low frequency comparisons between in situ dynamic height estimates and TOPEX/POSEIDON retrievals indeed indicated a reduction in sampling errors when additional TOPEX/POSEIDON data are considered around the mooring sites. For example, by grouping the altimeter data in 10 degree longitude by 3 degree latitude boxes around the mooring sites, and smoothing with 30-day Hanning filter, we found correlation greater than 0.95 and rms differences with the in situ data of less than 2 cm. However, increasing the size of the box does not systematically improve the low-frequency comparison, nor does the use of sophisticated optimum interpolation techniques.

In conclusion, our analysis suggests that the TOPEX/POSEIDON altimeter can provide instantaneous measurements of the sea surface dynamic topography accurate to 3-4 cm, depending on the choice of tidal correction scheme. This accuracy is remarkable, considering the complexity of the satellite sensor and tracking system, and the data processing and correction schemes required to derive oceanographically relevant information. Moreover, it is worth noting that the low-frequency comparison succeed in going below the 2-cm expected accuracy of the TOPEX/POSEIDON mission. Although based on only a limited amount of data in the western Pacific for a 6-7 month period, our results indicate that the TOPEX/POSEIDON data stream will prove to be an invaluable tool for seasonal to interannual climate studies in the tropical oceans where sea level is both a proxy for upper ocean heat content, and where geostrophic current variations are sensitive to small changes in sea level gradients.

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A Comparison of Coincidental Time Series of the Ocean Surface Height by Satellite Altimeter, Mooring, and Inverted Echo Sounder

Eli Joel Katz[1], Antonio Busalacchi[2], Mark Bushnell[3], Frank Gonzalez[4], Lionel Gourdeau[5], Michael McPhaden[4], and Joel Picaut[5]

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[1]Lamont-Doherty Earth Observatory of Columbia University/Palisades, NY 10964

[2]Code 970/Bldg. 22/Rm. 274/Laboratory for Hydrospheric Processes/NASA/Goddard Space Flight Center/Greenbelt, MD 20771

[3]AOML/NOAA/4301 Rickenbacker Causeway/Miami, FL 33149

[4]PMEL/NOAA/Bin C15700/Bldg. 3/7600 Sand Point Way, NE/Seattle, WA 98115-0070

[5]Groupe SURTROPAC/ORSTOM/BP A5/Noumea, New Caledonia

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 five days and between the altimeter and in situ measurements at periods greater than twenty days. The rms difference between any two modes of observation is consistently between 2 - 3 cm.

I. 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 1920's, the profile was estimated from sampling at a discrete number of depths with Nansen bottles and, by mid-century, 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) 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 note is to compare the result 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 note 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 TOGA-TAO moorings were deployed with additional instruments along 2°S to coincide with crossing points of two pairs of TP (TOPEX/Poseidon) 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 (one half meter) and only an average annual sea surface variation of 20 centimeters. These two conditions combine to make this a better than average location to

Table 1: Mooring and Sounder Locations

Observations at 156°E	Latitude (S)	Longitude (E)	Data Record Begins	Data Record Ends
Mooring	1° 59.2'	155° 53.8'	9/12/92	2/22/93
I.E.S. (A)	1° 59.2'	155° 53.3'	9/12/92	2/22/93
I.E.S. (L)	1° 59.6'	155° 54.0'	9/12/92	12/7/92
Observations at 164°E				
Mooring	1° 59.4'	164° 24.9'	8/26/92	3/11/93
I.E.S. (L)	2° 01.0'	164° 24.4'	8/26/92	3/22/93

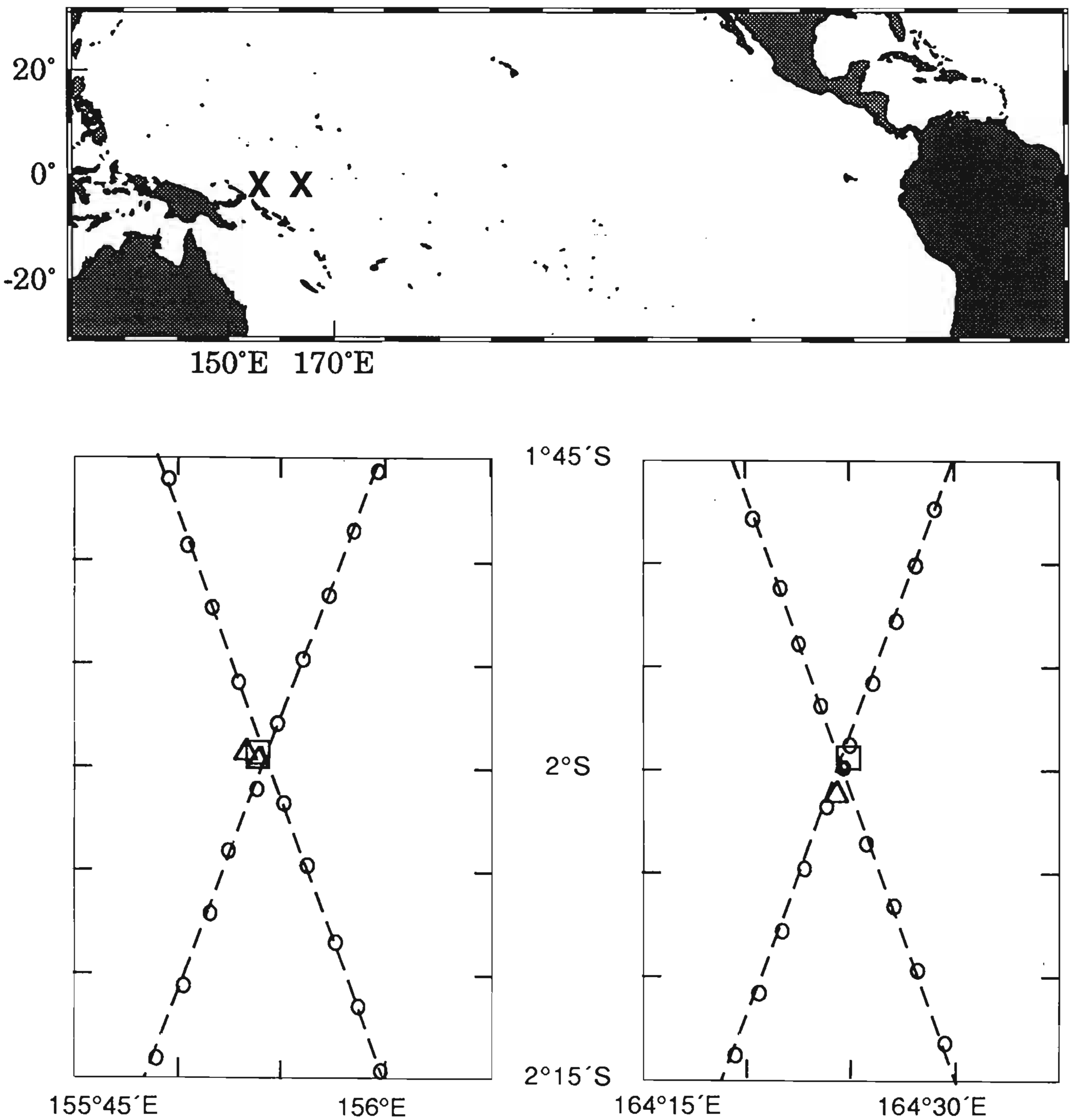

FIG. 1 Upper Panel: Site Location. Lower Panels: Location of Moorings (squares), Sounders (triangles) & Altimeter Tracks. Discrete altimeter reports along a typical path are located by circles. The passes crossing over the in situ observations are nos. 86 and 251 (left) and nos. 60 and 225 (right).

evaluate the altimeter which relies on models of the tide to remove what would otherwise be severe tidal aliasing.

II. Data Description and Reduction.

Each of the methods of observations respond 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 minutes), 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 will be discussed in a companion paper [Picaut et al., 1995] 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.

A. *Moorings*

The two moorings were deployed by the NOAA Pacific Marine Environmental Laboratory and the ORSTOM laboratory in New Caledonia. They consisted of ATLAS moorings (ten temperature sensors which record daily mean temperature between the surface and 500 meters), augmented with:

i. 5/12 (shallow/deep site) mini-temperature recorders, below 500 m and approximately 500 m apart, recording at 5-minute intervals.

ii. 16/11 SEACAT temperature-salinity sensors above 750 m with sampling intervals mostly at 5 mins.

iii. Pressure recorded at four depths between 300 and 750 meters (and from which the depth of each instrument was calculated) at 10-minute intervals.

All the time series were first interpolated to common 5-minute 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 meters, 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.

Surface dynamic height, relative to both 1000 dbars and the bottom-most 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. At the 164°E (deeper) site for example, the following is obtained:

	range (mm)	rms(mm)
0/1000 db	229.8	48.0
0/4400 db	251.8	50.3

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 upper panel of Figure 2, after low-pass filtering.

B. *Inverted Echo Sounder.*

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

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

where c is the sound velocity at depth z, z_o 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 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 the sounder signal, is resolved by the hourly sample rate and then removed by a low-pass filter.

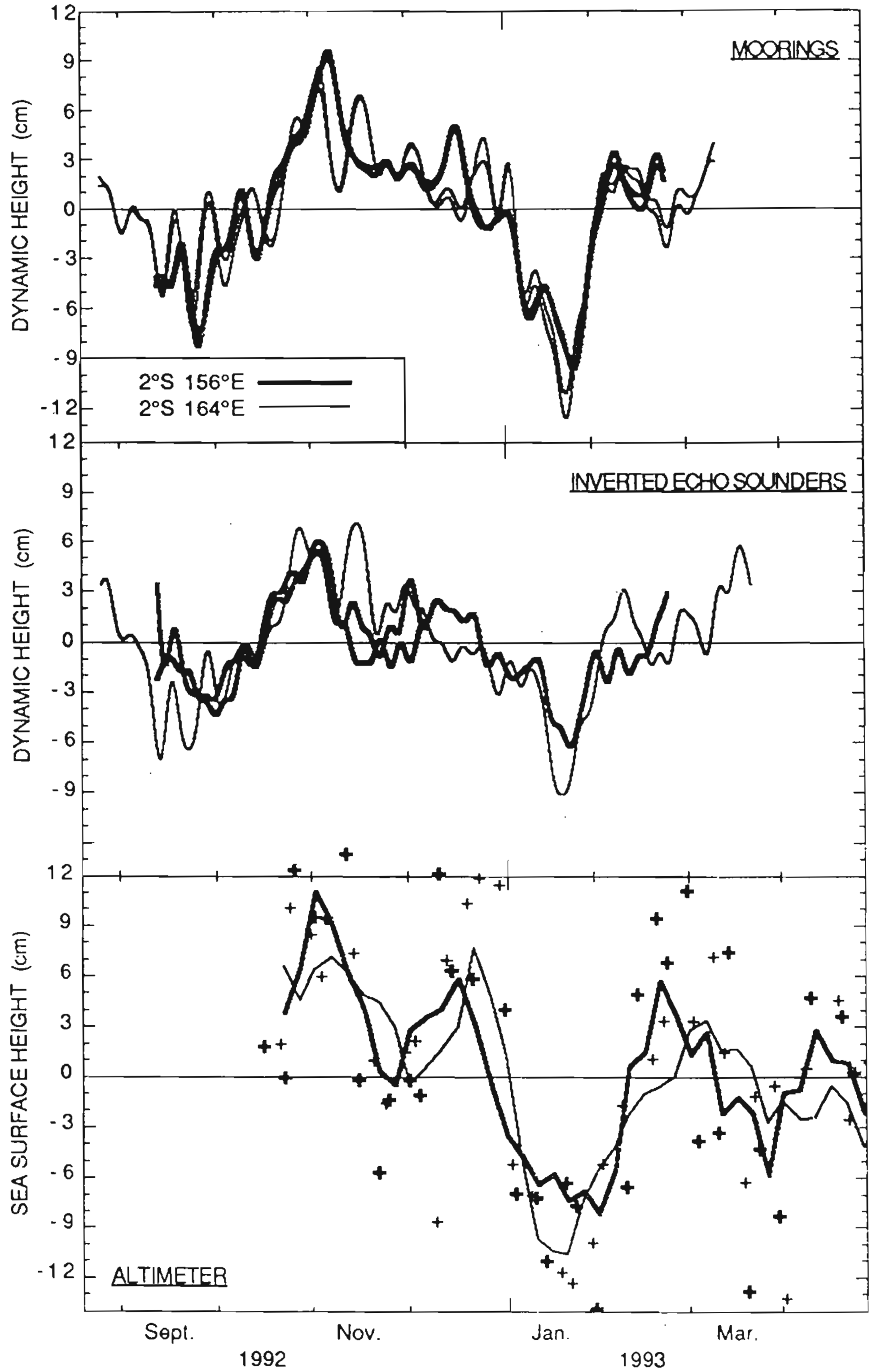

FIG. 2. Time Series of the Observations. The mean of each series has been removed. Upper Panel: Data from the two moorings after 5 day low-pass filtering. Both 0 re 1000 db and 0 re bottom are drawn, with only the slightest difference noticeable at the deeper site. Middle Panel: Data from the three sounders after 5 day low-pass filtering. After mid-Dec., only one of the sounders yielded data at 156°E. Bottom Panel: 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.

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

One set consists of thirty profiles in the vicinity of 2°S 165°E made from 1984 to 1991 (half during semi-annual cruises in January and July). The other is a time series of eighteen 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 1986/7 and 1991/2 El Niño episodes).

The slope of the regression line of the combined data set is -77.9 mm/msec with a standard error of 3.0 mm/msec. 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 to 1000 dbars 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/msec.

The derived regression is used to interpret the changes in total travel time recorded by the sounder after the sounders' time series were low-pass filtered. The resulting dynamic heights are shown in the middle panel of Figure 2. 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

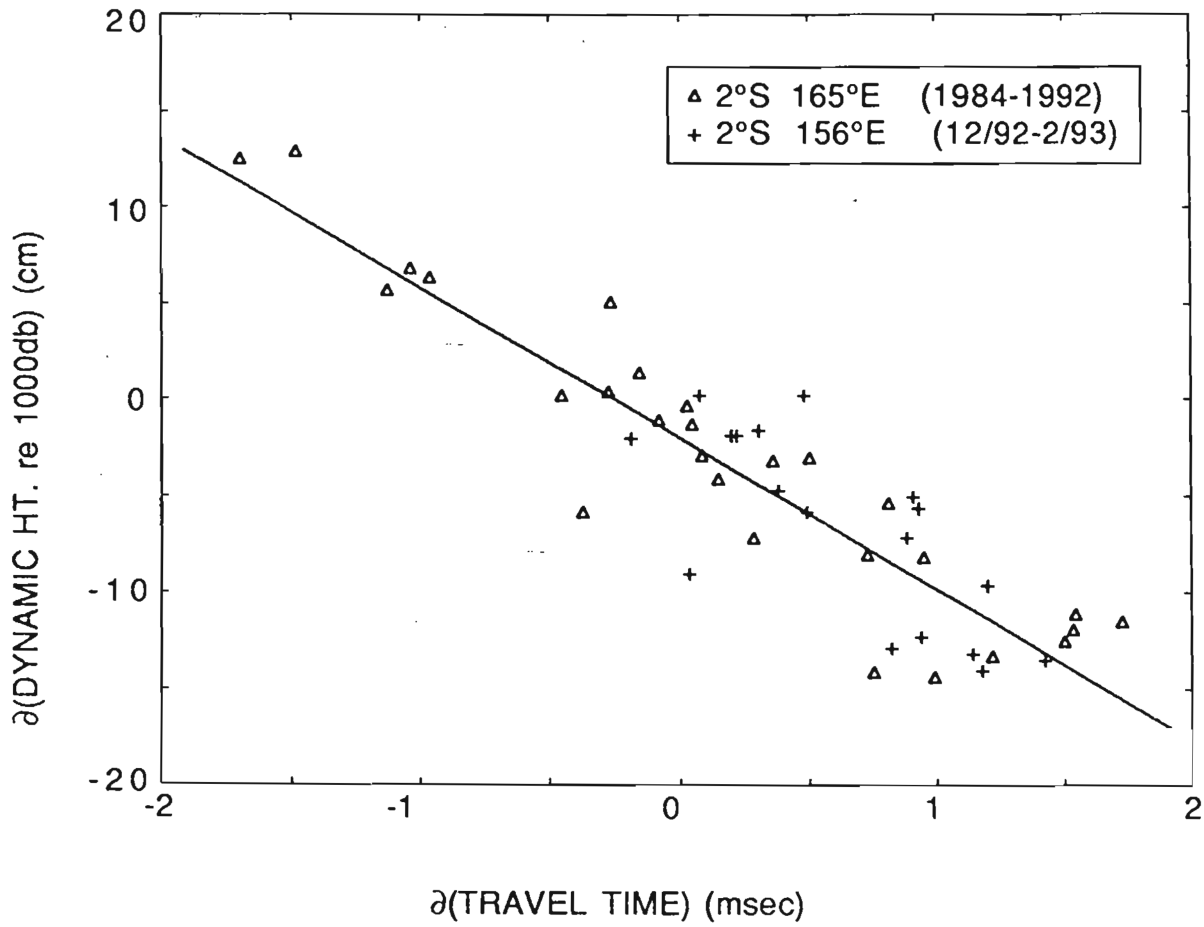

FIG. 3. Regression of the Dynamic Height of the Sea Surface on Acoustic Travel Time.

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.

C. *Altimeter*

The first usable data from TOPEX/Poseidon comes from passes over the observation sites on 13 October 1992, two months after launch and more than one month after the beginning of the in situ data. It is then continuously available from 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 ten 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 is exactly that obtained from the NASA MGDR discs (with corrections as recommended by the PO.DAAC Merged GDR Users' Handbook 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. Secondly, 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 M2 tide (frequency, f_{M2} = 1.932227 cycles/day) which dominates the barotropic tide in this area and the TOPEX sampling frequency (f_t) of (9.9156 days/cycle),$^{-1}$ the alias frequencies (f_a) are given by

$$f_a = (N \times f_t - f_{M2}), \text{ with N an integer.}$$

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 those frequencies.

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

III. Comparisons

A. *Sounders vs. 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 effectively convert 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 750m 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 spectral density 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 semi-diurnal tidal motion. At mid-frequency, 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 a f^{-2} behavior which, by extrapolation from six-year records in the tropical Atlantic [Katz,

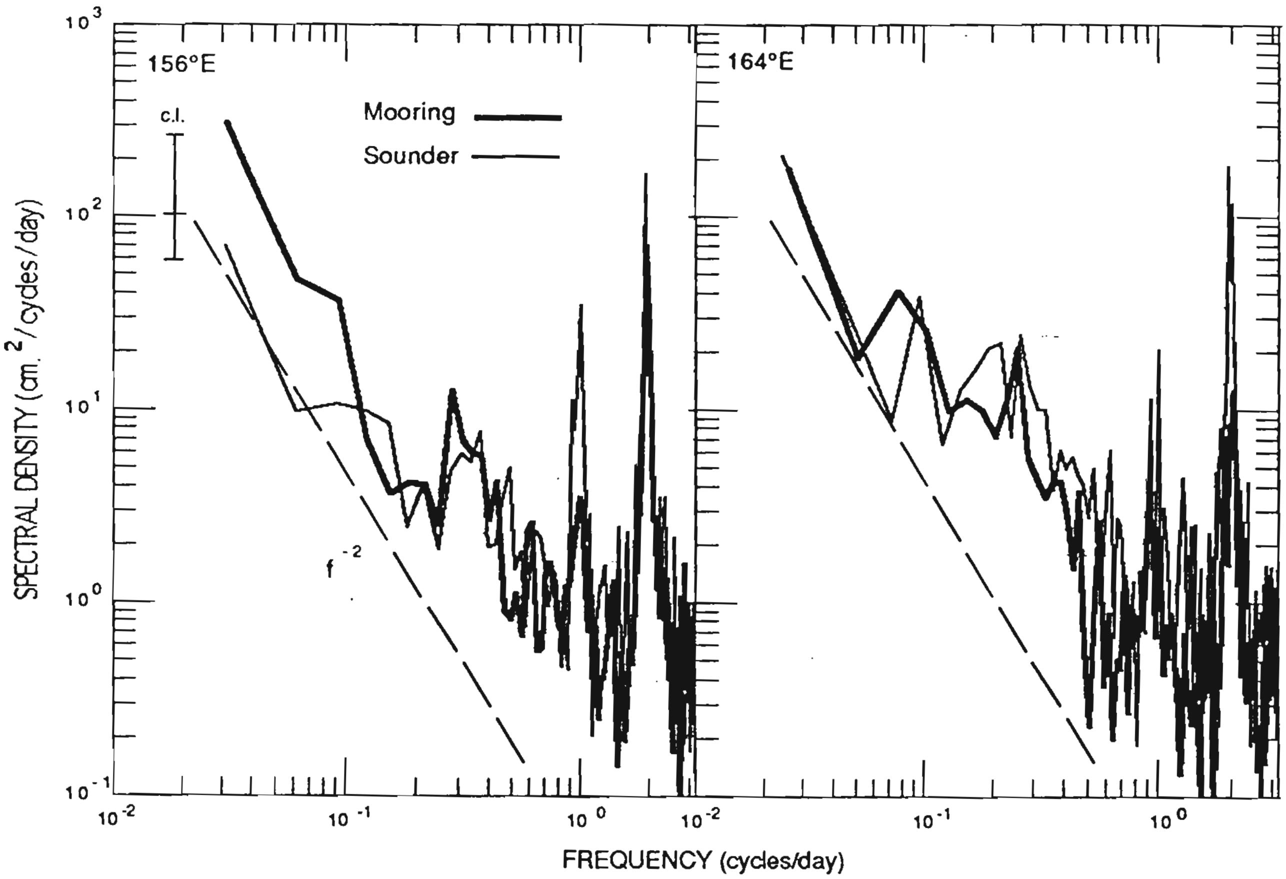

FIG. 4. Estimates of Spectral Density of the Sea Surface Height. Hourly data (except bihourly from sounder at 156°E) averaged over five frequency bands. The (95%) confidence limit (c.l.) shown is for 15 degrees of freedom (see text).

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 3x5 (frequency bands averaged), or 15, degrees of freedom. The 95% confidence limits for this is shown on the figure and the average spectral estimates are found not to be 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 Table 2. The correlation coefficient between the two signals at 164°E (L & 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 shorter, sounder versus sounder records (L & 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 differ by 50% at

Table 2: Correlation Between In Situ and Altimeter Observations

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

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

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

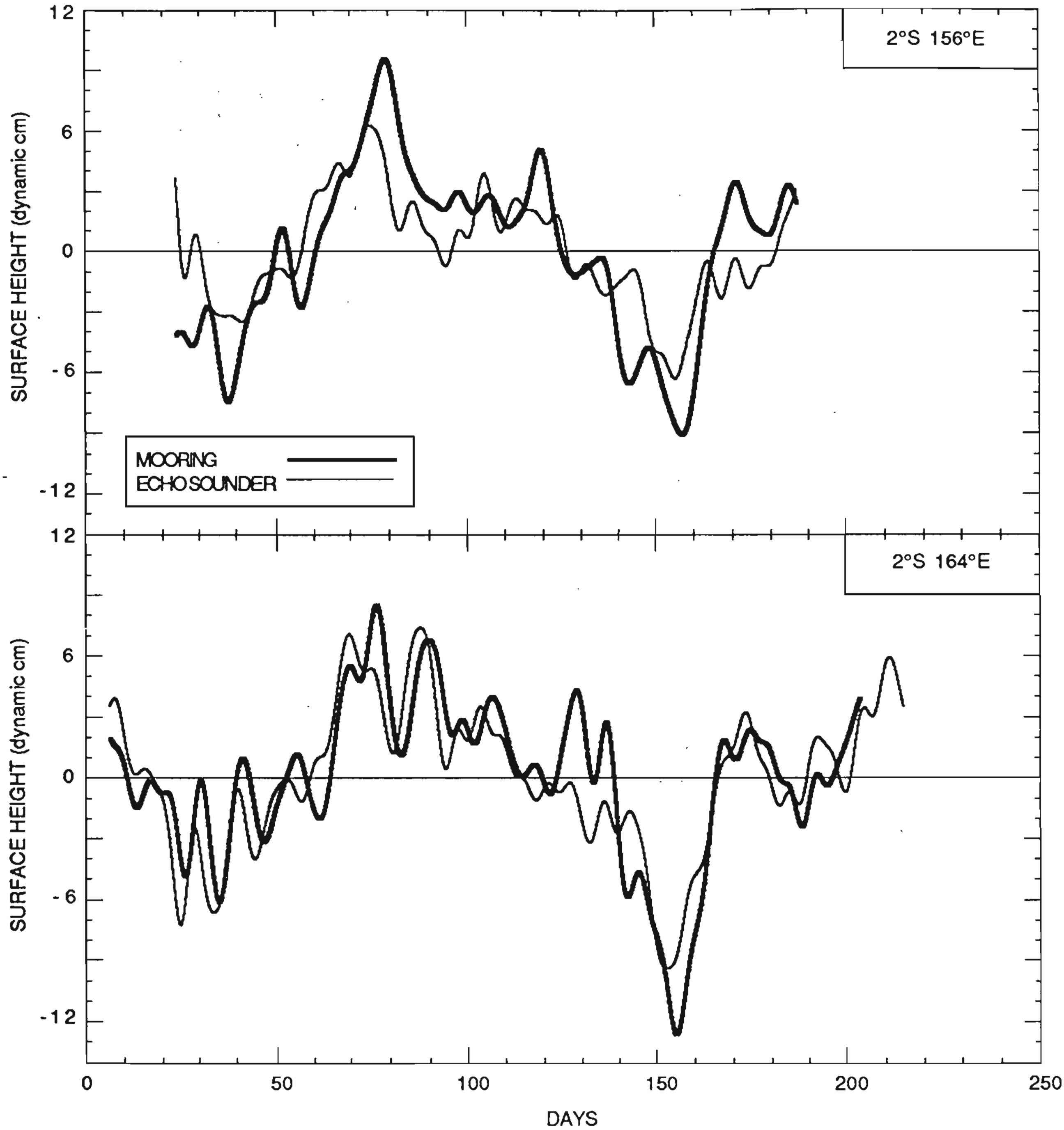

FIG. 5a. Comparison of the In Situ Observations at Both Sites. Redrawing of Figure 2 (upper two panels) to show tracking between sounder and mooring.

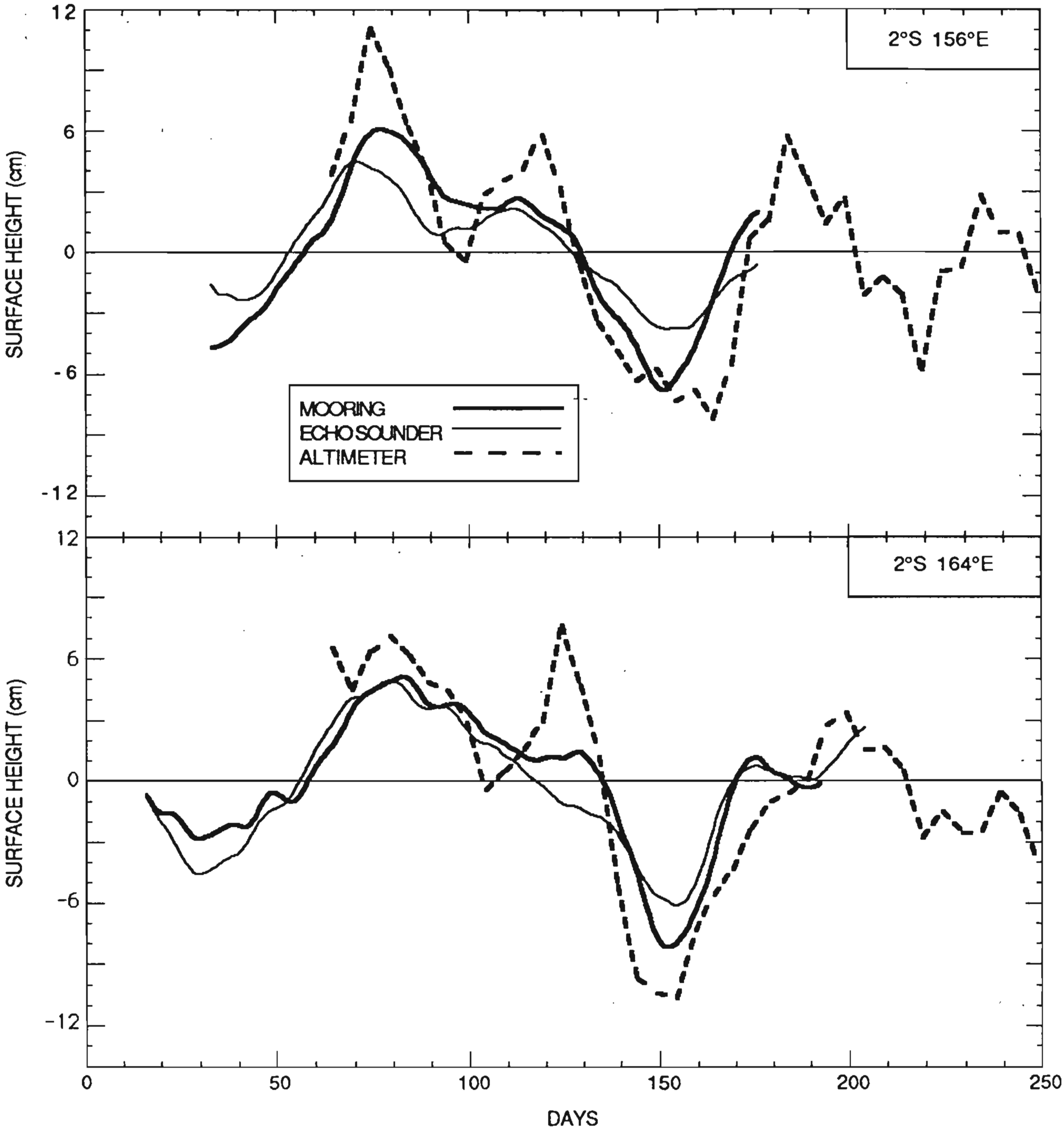

FIG. 5b. Comparison of the Three Observations at Both Sites. A running mean average over twenty days is plotted every five days.

156°E. Yet the reduction of variance and rms of their difference (62% and 2.5 cm) is comparable.

B. *Altimeter vs. Mooring/Sounder*

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

The rms height of the altimeter data is always higher than either of the in situ observations, but 63 to 77 percent 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.

IV. Summary and Conclusions:

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 snap shot, 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 Table 2, four comparisons between altimeter and in situ observations show an rms difference from 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 under sampled, 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.

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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 and 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 model [1990], based on GEOSAT altimeter data, and the earlier Schwiderski model [1981] 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, Seattle for the same time period and within one nautical mile of the sounder.

First we note the good agreement between the in situ methods: at worst a five cm. difference in amplitude and less than ten degrees in phase. The largest difference is with the M2 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 indicate no large or systematic differences, confirming what was deduced from the altimeter record itself, that tidal aliasing could at best introduce an uncertainty of a few centimeters, even in this area of relatively large amplitude, deep water, tides.

Cartwright and Ray have recently made available a revised model calculation based on early Topex/Poseidon data. It does not suggest any substantial change at the locations of concern here. For example, the largest amplitude constituent considered, M2 at 164°E, is revised to 544.7 mm, 143°.

TABLE 3: INVERTED ECHO SOUNDER DERIVED BAROTROPIC TIDAL CONSTITUENTS AND A BOTTOM PRESSURE SENSOR COMPARED TO TWO TIDAL MODELS (2°S 164°E). Amplitude (a) in millimeters, phase (p) in degrees relative to Greenwich.

	IES		Pressure Gauge		C/Ray		Schwirderski	
	a	p	a	p	a	p	a	p
O1	71.0	38	91.8	39	91.9	36	84.4	41
K1	136.4	49	157.6	54	151.9	54	146.5	62
N2	104.8	142	109.3	139	107.4	144	91.2	144
M2	469.2	148	526.0	139	522.4	141	482.7	142
S2	254.6	153	297.5	152	270.5	150	275.0	157

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Centre ORSTOM de Nouméa
B.P. A5 Nouméa Cédex, 98845, Nouvelle Calédonie