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Measuring heat storage changes in the equatorial Pacific: A comparison between TOPEX altimetry and Tropical Atmosphere-Ocean buoys

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Abstract. Heat storage variations in the equatorial Pacific have been studied from December 1992 through February 1997, using sea level data from the TOPEX altimeter and temperatures measured by 42 tethered buoys that are part of the Tropical Ocean-Atmosphere (TAO) array. The TOPEX measurements are converted to heat storage anomalies using a coefficient determined from mean climatological values. For 30-day averages the two measurements agree well over most of the region, except for the southwestern quadrant of the warm pool and a small region of the north-central equatorial Pacific. In the southwestern quadrant the TOPEX measurements indicate a smaller long-term heating rate than the TAO measurements, differing by as much as 30%. After examining conductivity-temperature-depth data in this region, it appears that the difference is due to a change in ocean salinity which is reflected in the TOPEX sea level measurements but not in the TAO heat measurements. The signal in the north-central region is predominately at an annual period, but there is not enough external measurements to determine what the source of the difference is. In the remainder of the equatorial Pacific, the agreement between the data suggests that the TOPEX measurements can be used to measure heat storage variations in the upper layer with reasonable accuracy. Thus TOPEX altimeter data can provide information about the heat budget of the equatorial Pacific in regions where there are few or no direct measurements.

1. Introduction

The tropical Pacific Ocean plays an important role in the global oceanic heat budget. Normally, the trade winds push water westward, where it forms a large warm pool. The strong Kuroshio Current carries this warm water away from the equator and transfers the heat to the atmosphere and other parts of the ocean thousands of kilometers away from the tropics. Occasionally, normal conditions change and the northward advection of warm water slows while the eastward advection increases: the El Niño/Southern Oscillation (ENSO). This change in the tropical Pacific heat storage can have significant consequences in many other parts of the globe [e.g., *Philander,* 1990]. Measuring the variations in the heating of the tropical Pacific can thus be important for studies and predictions of climate in other parts of the world.

Traditionally, the heat has been measured by in situ temperature recorders, such as expendable bathythermographs (XBTs). Over the last decade, the National Oceanic and Atmospheric Administration (NOAA) has placed nearly 70 moored buoys in the tropical Pacific as part of the Tropical Atmosphere-Ocean (TAO) program to record temperatures on a continuous basis [*McPhaden,* 1993]. While this is an improvement over scattered XBT casts, the buoys are still widely spaced longitudinally and suffer from occasionally long periods of missing data. Also, the network extends only to ± 10° from the equator, so it does not monitor heat changes over the entire tropical region.

In a previous study [*Chambers et al.,* 1997], we presented a method of computing heat storage anomalies directly from satellite altimeter measurements of sea level using a linear regression

$$\Delta H = \gamma \Delta\eta = \frac{\rho c_p}{\alpha} \Delta\eta, \qquad (1)$$

where ΔH is the heat storage anomaly in J m^{-2}, ρ is the density of the seawater, c_p is the specific heat of seawater, α is an averaged thermal expansion coefficient, and $\Delta\eta$ is the sea level anomaly computed from the altimeter data. Since altimetry is nearly global and has a more dense spatial resolution than the TAO array, it presents a new way to monitor changes in the oceanic heating that can supplement in situ measurements.

The preliminary results using altimetry to measure heat storage changes are encouraging. *White and Tai* [1995] regressed altimetry sea levels against in situ heat storage measurements from XBTs and found correlations greater than 0.6 over much of the northern hemisphere. *Chambers et al.* [1997] found that using a coefficient computed directly from climatological data gave equally good correlations. *Wang and Koblinsky* [1997] have found that heat storage derived from TOPEX altimetry agreed well with coincident XBT data in the North Atlantic.

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In this study, we will compare the heat storage variability inferred from TOPEX altimetry in the equatorial Pacific with that measured by in situ buoys which are part of the TAO program. We will first examine the errors in the individual measurements, as well as the expected agreement between the TOPEX and TAO measurements of heat storage. Then, we will compare monthly averaged TOPEX and TAO measurements at each of the TAO buoy sites to determine where the variability signal measured by TOPEX is most strongly influenced by changes in the upper ocean heat storage. We will point out places where the residuals are larger than the expected differences, and comment on possible sources for the differences. Based on the results from this study, one will be able to determine where the altimetric measurements of heat storage are most representative of upper ocean changes in order to use the data for studies concerning the heat budget of the equatorial Pacific.

2. Data Processing

For this study we have used data over the time period from January 1993 through February 1997. The TOPEX altimeter data (repeat cycles 10 to 161) are from the first release Geophysical Data Records (GDRs) and include all geophysical corrections, including the inverted barometer correction [*Callahan,* 1993]. Data from the separate POSEIDON altimeter are not used. Several changes have been made to the data to update models and correct errors. The GDR orbits have been replaced with those computed with the JGM-3 gravity field model [*Tapley et al.*, 1996], the ocean tide model has been replaced with the University of Texas Center for Space Research 3.0 model [*Eanes and Bettadapur,* 1995], and the pole tide has been corrected. The data have also been corrected to fix an error caused by the misapplied oscillator correction before cycle 132, using a time series provided by D. Hancock and G. Hayne at the Wallops Flight Facility. We have not applied the drift detected by the internal calibration mode to the data at this time [*Hayne et al.*, 1994], because studies indicate that the TOPEX measurements show slightly better long-term agreement with tide gauge data when the internal calibration correction is not used [*Mitchum*, 1998; *Chambers et al.*, 1998a]. However, the size of this correction is small, only a few millimeters root-mean-square (rms), so it will not affect most of the results discussed here.

Daily averaged temperature measurements at fixed depths in the ocean were obtained from tethered buoys which are part of the Tropical Atmosphere-Ocean array. There are currently 75 buoys in the data set. Five were immediately removed because they drifted more than 100 km between 1992 and 1997, most likely due to a broken tether. Although many of the sites make measurements to 500 m depth, we found that there were long data outages at the 400 and 500 m depths at many of the sites. Because of this, we computed the integrated heat storage (H) to only 300 m depth, since most sites had nearly complete records to this depth. The total heat content was computed from averaged-daily temperatures (T) at each level (h) as

$$H_i = \int_{-300}^{0} \rho c_p T_i \, dh, \qquad (2)$$

where i indicates the day, and ρ and c_p are computed using the temperature and pressure level from the buoy and monthly salinity values from *World Ocean Atlas 1994* [*Levitus and Boyer*, 1994]. After computing the heat storage, 20 sites were eliminated because they had numerous extended data outages. Ten of these had less than 1 complete year of observations. Two more sites were removed because of a large change in the heat storage after a data outage, suggesting a problem with one or more of the temperature sensors. Six additional sites were removed because there were fewer than 20 TOPEX observations near them for each 10-day repeat cycle. This left 42 sites for our analysis (Figure 1).

Because each of these data have different references, we can only compare the variations in the heat storage by computing anomalies, or deviations about a mean. For the TAO data this is a simple calculation, done by removing a long-term average of the data at each buoy from the daily value. The computation of the anomaly for the TOPEX measurements is slightly more difficult, due to the fact that the altimeter measurements are not made at a single point like a TAO buoy but are scattered over a small area due to cross-track drift and the 1-s sampling rate. Since the altimeter directly measures the sea surface height, including the marine geoid, this can cause significant errors around steep geoid gradients near trenches and seamounts [*Brenner et al.*, 1990].

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

The TOPEX sea level anomaly data are converted into heat storage anomalies following the procedure outlined by *Chambers et al.* [1997], using (1). In this study, we have computed ρ, c_p, and α at pressure levels from 300 m to the surface, using the monthly averaged values of temperature and salinity from the *World Ocean Atlas 1994*, and the international equation of state for seawater [*UNESCO*, 1981]. A value of the coefficient γ is computed from ρ, c_p, and α at each level, then the average integrated value is computed over a regular 1° grid.

To compare the heat storage anomalies, we have filtered the data in time and space to a comparable grid. The TAO data were averaged over 10 days to obtain a single value commensurate with the TOPEX repeat cycle. TOPEX data for each repeat cycle were averaged in a 4° longitude by 2° latitude box centered on each buoy, to average out random noise and to improve the accuracy of the sea level measurement. Although this filters out short-wavelength fluctuations in the altimetry data, heat storage in the tropics is predominately at long wavelengths. This processing resulted in two time series at each buoy, one for the TAO data and one for the TOPEX data, with a time interval of one TOPEX repeat cycle. The time series were also low-pass filtered with a running-mean boxcar filter with a window of three repeat cycles (30 days) to smooth over high-frequency variations and single cycle dropouts.

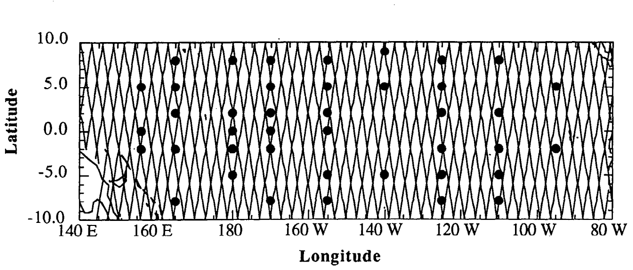

Figure 1. Location of TAO buoys (circles) with TOPEX ground track.

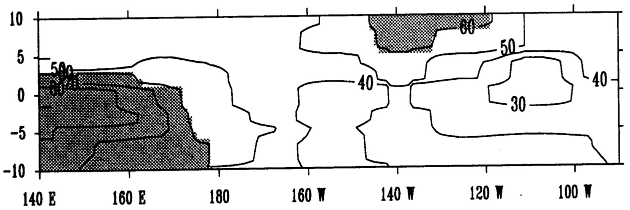

Figure 2. The rms difference of TOPEX and TAO measurements. The contour interval is 10 x 10^7 J m^{-2}, and values larger than 60 x 10^7 J m^{-2} are shaded gray. The grid has been optimally interpolated using a technique described by W. S. Kessler, M. J. McPhaden, and D. McClurg at PMEL (1996).

3. Discussion of Results

At this level of smoothing, the TOPEX sea level data have an estimated accuracy of 2 to 3 cm [*Cheney et al.*, 1994]. In the tropical Pacific the average value of γ is 1.4 x 10^{10} J m^{-3}, implying that the error in the heat storage anomaly from TOPEX due to measurement errors is smaller than 42 x 10^7 J m^{-2}. For the TAO data the largest source of error is in the temperature measurements. The temperature measurements have been found to have significant drift on some buoys, with an overall rms difference of 0.09°C compared with earlier calibrations after a buoy is recovered [*Freitag et al.*, 1994]. There can also be significant interannual salinity changes in the tropical Pacific, especially in the western portion of the basin [*Delcroix and Henin*, 1991], but this will not have a significant effect on the calculation of stored heat from the TAO buoys. It will, however, cause an additional signal in the TOPEX data that is not related to heat storage, which will cause a disagreement between the TOPEX and TAO measurements. This will be discussed in more detail later in this section. For the moment we will base our estimated error on the temperature error in the TAO data alone. Assuming that the error is 0.09°C and that it acts in the same direction at every level, we find a maximum error in the heat storage anomalies from the TAO data to be 23 x 10^7 J m^{-2}, comparable to the errors estimated by *Wyrtki and Uhrich* [1982] for XBT data.

However, this is only an estimate of the error in the measurement of the upper ocean heat storage. Because the TAO measurements extend to only 300 m, there is an additional sampling error compared with the sea level measurements which reflect changes in the heating of the whole water column. Although the exact size of the variability below 300 m is unknown, we can estimate it by examining the average temperatures in the *World Ocean Atlas 1994*. The average standard deviation in heat storage across the equatorial Pacific from 300 to 1000 m (the maximum depth with monthly data) is 15 x 10^7 J m^{-2}. This underestimates the sampling error, since it does not take into account variability below 1000 m, or variability due to interannual fluctuations. Thus we believe the error in the heat storage of the total water column from the TAO data is about 27 x 10^7 J m^{-2}, based on the root-sum-square (rss) of the instrument and sampling errors.

This suggests that the time series should agree to within 50 x 10^7 J m^{-2}, assuming that the data errors are uncorrelated. If the sea level variations are dominated by upper layer heat storage variability, then the difference between the TOPEX and TAO data should be less than this value. If the difference is more, it suggests that there is another source of sea level variation in addition to heat storage, and that TOPEX data should be used with caution in estimating heat storage in these areas.

The rms of the differences between the TOPEX and TAO data are less than 50 x 10^7 J m^{-2} over much of the basin (Figure 2) except for two regions: in the warm pool southwest of the equator and in the central Pacific from 160°W to 120°W north of 5°N. The average rms is 48 x 10^7 J m^{-2}. Correlations are greater than 0.7 at almost every site (Figure 3), including those with high rms values. Only a few sites have correlations less than 0.7, and they are primarily in the southeastern tropical Pacific, a region of low variability.

Figures 4a and 4b show the TOPEX and TAO time series at 15 of the 42 buoys. Since several of the buoys are relatively close together and have similar signals, we have selected these as a sample, ranging from the best agreement (Figure 4b, 2n110w) to the worst (Figure 4a, 0n156e). The nomenclature used here for a buoy location is a character string with the latitude and longitude; thus buoy 2n110w is located at 2°N, 110°W. The two data sets are well correlated over a broad range of frequencies. For instance, the TOPEX and TAO measurements indicate similar changes in long-period heat storage associated with the El Niño events of 1993 and 1994 (buoys 2s95w, 0n155w, 0n170w). Intraseasonal fluctuations are also in agreement, most notably at 5n155w during fall 1993 and 1996, 9n140w during 1995 and 1996, and at 5s110w during 1993, 1995 and 1996. At 8n165e, both data indicate a large change in the annual minimum from 1995 to 1996.

However, as the rms and correlations indicated, there are some significant differences. When we examined the time series in the regions where the rms was higher than 50 x 10^7 J m^{-2}, we noticed that for the sites in the warm pool (e.g., buoys 0n156e and 2s165e in Figure 4a) the difference was caused mainly by a difference in the long-term heat rate. A plot of the average difference between the TOPEX and TAO measurements in the southwestern Pacific indicates a large relative drift between the two (Figure 5), implying that the long-term slope of the TOPEX data is consistently smaller than that of the TAO data. At buoy 0n156e, which has the largest relative rms value, the long-term slope of the TOPEX data is about 30% smaller than the slope of the TAO data. The difference in the long-term trends (TOPEX relative to TAO) is consistently large and negative in this region, whereas in the rest of the basin the difference is between ± 5 W m^{-2} (Figure 6). If the difference in the long-term trend were removed, the rms of the differences at 0n156e would drop to below 48 x 10^7 J m^{-2}, consistent with the other regions.

The difference in the long-term trends is not due to an error in the altimeter, because there is no significant difference in the long-term trends measured by TOPEX and tide gauges in this region (Figure 7). We have found no extreme drift in any of the temperature sensors relative to other sensors on the TAO buoy, and it is unlikely that all the buoys in the warm pool would have approximately the same error. Although the tide gauge comparisons suggest there may be a small drift in the TOPEX altimeter [*Mitchum*, 1998; *Chambers et al.*, 1998a], the size of this signal is only about -2 mm yr^{-1}, or -1 W m^{-2} in inferred heat storage rate. If the buoys in the southwestern quadrant are eliminated from the average, the mean heat storage rate difference between TOPEX and TAO in the rest of the region is about -0.9 W m^{-2}, consistent with the observed drift with respect to the tide gauge data. Thus we believe that the larger slope in the

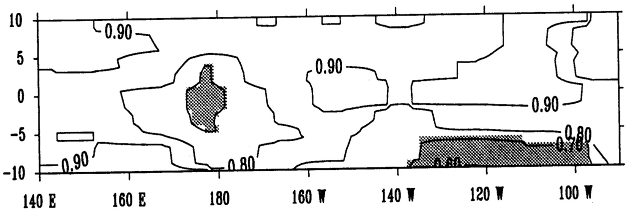

Figure 3. Correlation between TOPEX and TAO measurements. The contour interval is 0.1, and values less than 0.7 are shaded gray. The grid has been interpolated as in Figure 2.

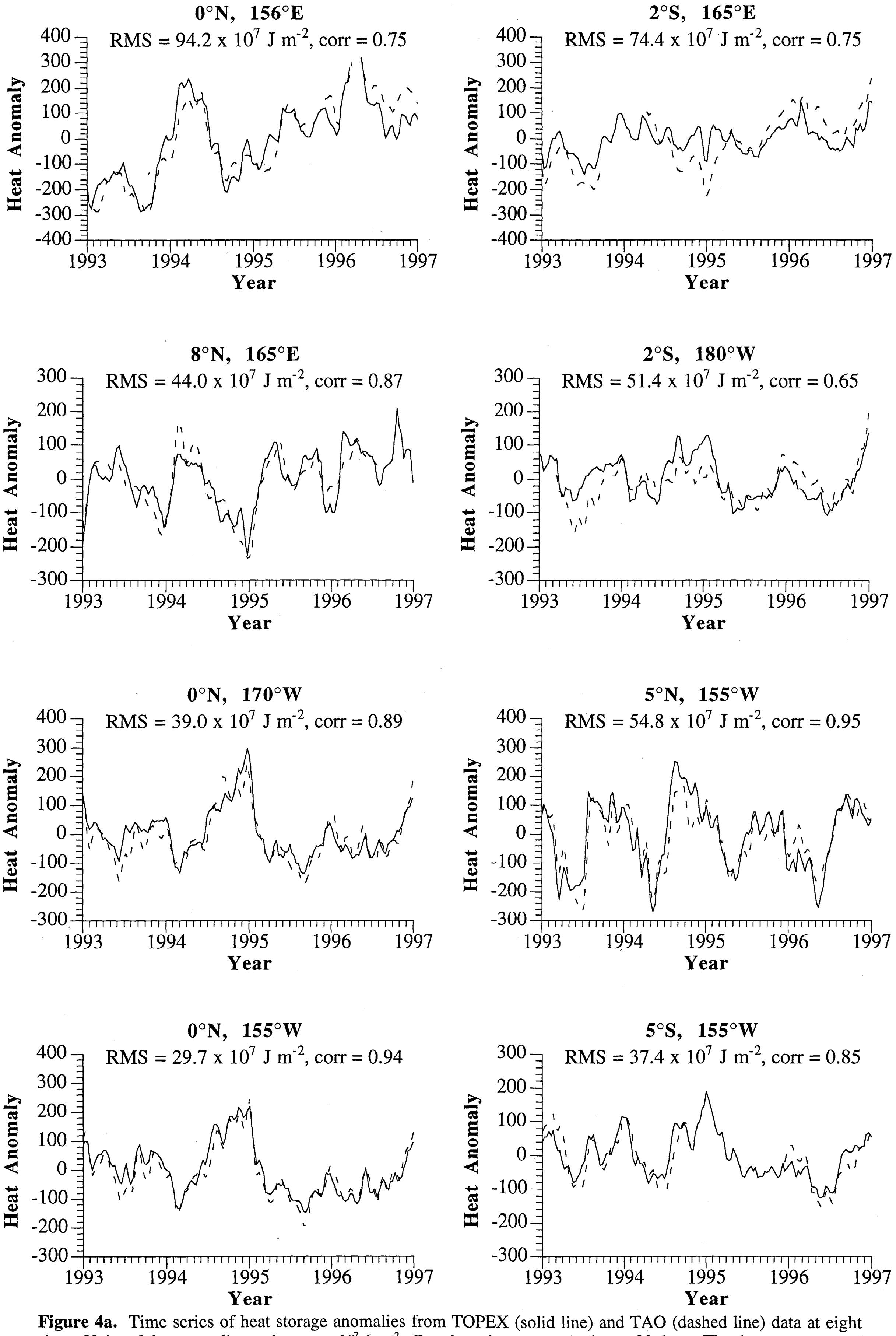

Figure 4a. Time series of heat storage anomalies from TOPEX (solid line) and TAO (dashed line) data at eight sites. Units of the anomalies and rms are 10^7 J m^{-2}. Data have been smoothed over 30 days. The dates are centered under January 1 of each year.

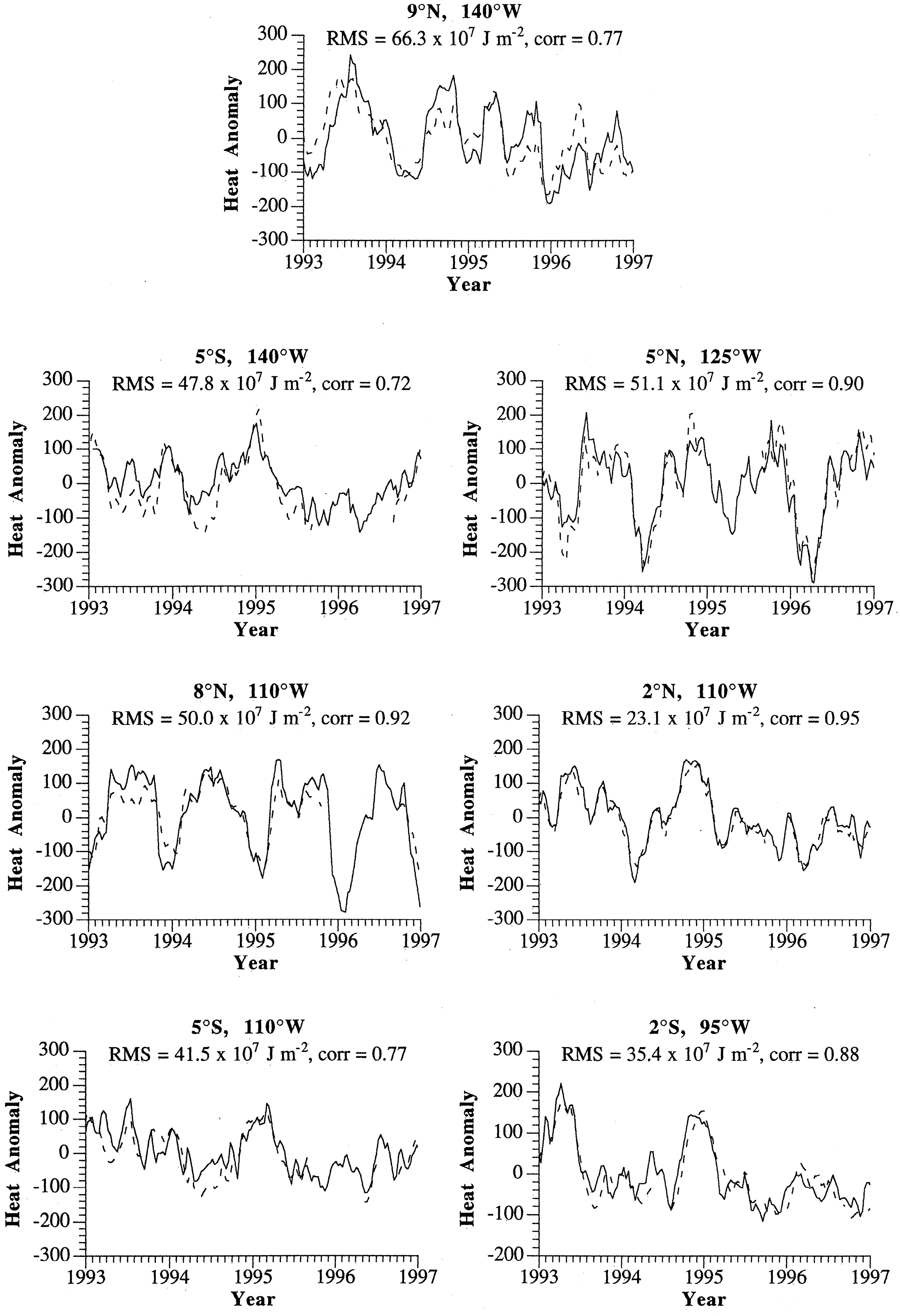

Figure 4b. Time series of heat storage anomalies from TOPEX (solid line) and TAO (dashed line) data at seven sites. Units of the anomalies and rms are 10^7 J m^{-2}. Data have been smoothed over 30 days. The dates are centered under January 1 of each year.

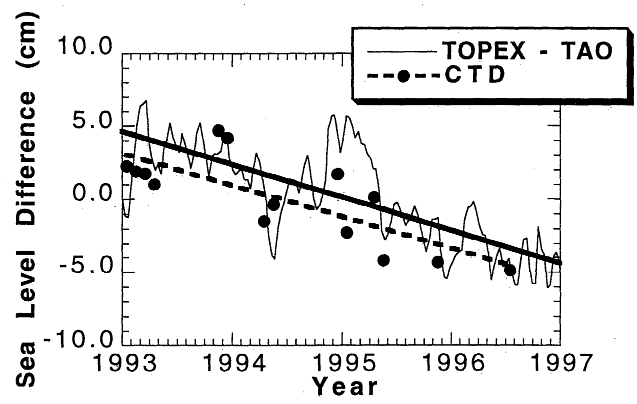

Figure 5. Difference in TOPEX sea level minus TAO sea level (solid curve) and CTD sea level with true salinity minus CTD sea level with climatology salinity (solid circles). Both time series used all available data in the area 10°S to 0°N, 140°E to 180°E and were smoothed over 30 days. The solid line is the best fit linear trend for the TOPEX-TAO data, while the dashed line is the best fit linear trend for the CTD data. The dates are centered at January 1 of the year.

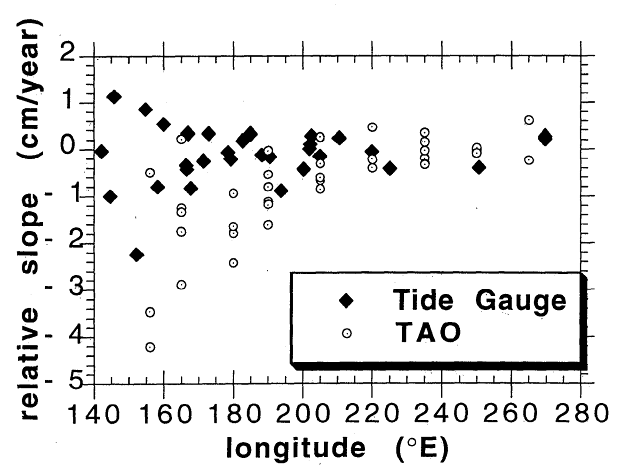

Figure 7. Difference in long-term trends between TOPEX and TAO (circles) and TOPEX and tide gauges (diamonds). The TAO heat storage values have been reduced to sea level variations using (1).

southwestern quadrant is indicative of a sea level change which is not connected with heat storage in the upper layer.

One possible cause for the signal is a change in the salinity in this region, as mentioned earlier. An increase in salinity will cause water to be heavier and it will tend to counteract part of the thermal expansion due to increased warming; a decrease in salinity will cause water to be lighter and it will tend to reinforce the thermal expansion due to increased warming. Observations in the warm pool indicate that there are large interannual variations in salinity connected with ENSO, with salinity increasing from the El Niño to the La Niña phase of the ENSO cycle [*Delcroix and Henin*, 1991]. Since the cycle from 1993 to 1996 was from El Niño to La Niña, we investigated whether this could account for the discrepancy between the TOPEX and TAO measurements. Conductivity-temperature-depth (CTD) casts in this area were obtained from the NOAA Pacific Marine Environmental Laboratory (PMEL) and were used to compute sea level (dynamic topography) anomalies using the measured salinity (analogous to the TOPEX measurements) and the climatological salinity (analogous to the TAO measurements). The two sea level measurements were then differenced to obtain a residual similar to the TOPEX minus TAO results in Figure 5 (e.g., sea level with real salinity minus sea level with climatological salinity). The CTD data were averaged over monthly intervals similar to the smoothing performed on the TOPEX and TAO data, then averaged over the region 10°S to 0°N, 140°E to 180°E.

Although there are only 14 CTD differences over the 4-year span, they are distributed evenly enough in time that a linear trend is apparent (Figure 5). In fact, the relative trend is -2.2 cm yr^{-1} for each case, indicating that the "true" sea level rose at a slower rate than the rate implied by the changes in heat alone. This suggests that most of the linear drift between the TOPEX and TAO measurements in the southwestern quadrant is due to an increase in the ocean salinity. There is not enough CTD data to determine if the higher frequency variations in the differences may be due to salinity variations as well.

The second region where the rms of the comparisons is high is in the central Pacific north of the equator. There is not a significant difference in the long-term trends in this region. When we examined the differences at other frequencies, we found significant variability at an annual period (Figure 8). Again, we do not believe that this is caused by an error in the TOPEX measurements. Although comparisons with tide gauges show that TOPEX disagrees with some sites with an annual period, the maximum amplitude of this difference is only 2 cm. This will account for only a 28 x 10^7 J m^{-2} amplitude in the difference of heat storage, much less than what is observed. While climatological surface salinity in the area does have a small annual amplitude [*Chambers et al.*, 1997], direct CTD measurements in this area are even scarcer than in the western Pacific and there are not enough measurements to discern an annual signal if one exists. On the other hand, the signal could be due to another type of forcing, such as variations in deep currents below the extent of the TAO data. It is impossible to tell with the limited amount of data available at the moment.

4. Conclusions

Heat storage anomalies inferred from TOPEX altimetry using a coefficient based on climatological data agree with those computed from direct temperature measurements made by TAO buoys with an rms difference of less than 50 x 10^7 J m^{-2}.

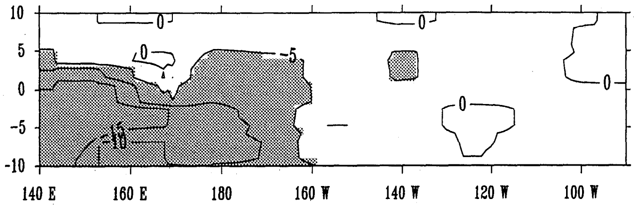

Figure 6. Difference in long-term trends between TOPEX and TAO measurements. The contour interval is 5 W m^{-2}, and values more negative than -5 W m^{-2} are shaded gray. The grid has been interpolated as in Figure 2.

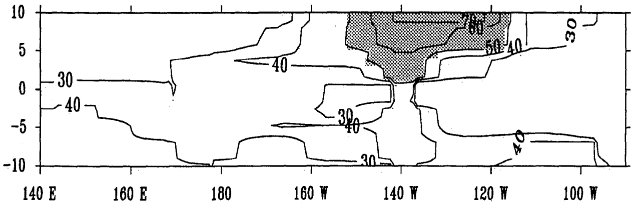

Figure 8. Annual amplitude of difference between TOPEX and TAO measurements. The contour interval is 10 x 10^7 J m^{-2}, and values larger than 50 x 10^7 J m^{-2} are shaded gray. The grid has been interpolated as in Figure 2.

Significant differences occur at long periods in the western Pacific and at annual periods in the central Pacific north of 5°N. In the western Pacific, the long-term heat storage rate inferred from TOPEX is as much as 30% smaller than that inferred from the TAO data. In the central Pacific, the difference between the TOPEX and TAO measurements are dominated by an annual variation.

There is evidence that the differences in the western Pacific are due to interannual fluctuations in the salinity associated with ENSO. If this is so, then it suggests that a combination of TOPEX altimetry and in situ temperature measurements such as that from the TAO buoys or XBT data could be used to monitor variations in ocean salinity. This would be a useful measurement, considering the relative scarcity of in situ salinity measurements. In the north-central equatorial Pacific there is not enough independent data to determine why the TOPEX and TAO measurements disagree with a pronounced annual oscillation. More analysis needs to be done to determine the cause of the signal. Because of the limited amount of real data in this area, the only insight may come from numerical models.

Over the remainder of the equatorial Pacific, though, the results of this study indicate that sea level variations are driven almost entirely by changes in the upper ocean heat storage. This suggests that the TOPEX data are well suited to supplement in situ data where such data are not available in this region. This analysis has shown several instances where the annual variability of heat storage has differed significantly from the mean signal during times when in situ observations were not available but altimetric observations were, such as at buoy 5n125w and 8n110w in Figure 4b.

It appears that linear heat storage rates over several years can be estimated from the altimetric data with an accuracy of better than 5 W m^{-2} over all regions of the equatorial Pacific except the southwestern quadrant west of about 170°W. The TOPEX data can even be used in the southwestern Pacific, if one assigns the long-term heat storage rate a higher error (of the order of 10 to 20 W m^{-2}) because of the salinity signal. Thus the TOPEX measurements can be used directly to monitor long-term changes in the upper ocean heat content with a high degree of accuracy, especially in the eastern Pacific. This is especially important in global climate predictions, since this is the part of the Pacific where interannual signals related to El Niño are most pronounced.

Finally, we should remark that while this investigation has shown good agreement between altimetry and heat storage in the equatorial Pacific, more work needs to be done examining the relation outside of this region. Although it has been shown that the TOPEX measurements averaged over the North Pacific and North Atlantic agree well with direct measurements [*White and Tai*, 1995; *Chambers et al.*, 1997], comparisons with real measurements at smaller scales has only been done in limited regions, such as the northwest Atlantic [*Wang and Koblinsky*, 1997] or the equatorial Pacific, as in this study. Further investigation using XBT data from ships of opportunity is needed to determine the amount of sea level signal due to heating variations in other parts of the oceans. However, when this has been done, satellite altimetry could become a useful tool to study changes in the global ocean's heat budget.

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