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Estimates of Heat Content Variations from Sea Level Measurements in the Central and Western Tropical Pacific from 1979 to 1985

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ABSTRACT

A method is developed to estimate oceanic heat content (0–300 m) variations from sea level measurements in the tropical Pacific. To this end, statistical relationships between heat content and steric level, used as a surrogate variable for the sea level, are derived from climatological data. These relationships are then applied on independent datasets and the predictive ability of the method is determined regionally by comparing heat content estimated from XBT and sea level measurements recorded in three tropical Pacific islands (Christmas, Fanning and Truk) during the 1979–85 period.

Good qualitative agreements are found between the two heat content estimates with correlations $R = 0.78$ to 0.94 and rms differences of average temperature of 0.25° to 0.50°C over an observed range of 6°C. Quantitative disagreements are observed in the central Pacific during the fall 1982 (El Niño) period. These deficiencies in the method are found to be primarily due to intense and unusual salinity fluctuations at the surface which notably contribute to sea level variations. The difference between heat content variations deduced from sea level and calculated ones (from XBT) is significantly correlated ($R = 0.54$) with these sea surface salinity fluctuations.

For the investigated areas, the adopted method thus indicates that: 1) 2- and 3-month averaged sea level measurements can account for 61% to 88% of the 0–300 m heat content variations and, 2) special attention is required in its application when intense and unusual sea surface salinity anomalies occur.

1. Introduction

The variability of the tropical Pacific ocean heat storage has received considerable attention in recent years since it is an important parameter for the study of the upper ocean thermal structure (e.g., White et al., 1985) and it plays an essential role in sustaining the "chain reaction" that generates an El Niño event (Wyrtki, 1985; Cane et al., 1986). It is thus, in this sense, a major component of the earth's climate. Due to the lack of data, this variability has generally been described in terms of climatological means obtained from temperature profiles collected from a large number of different ships, over many years, in different seasons and locations. Although ship-of-opportunity programs have provided new insight into the oceanic heat storage variability in the last decade, this is mainly true along shipping routes obtained at specific times. As the sea level variations can be easily obtained from island tide gauges and, on a global basis, from future satellite altimetry monitoring, numerous previous investigations have dealt with its relations with heat content variability or basic oceanographic parameters of interest to ocean monitoring (Patullo et al., 1955; Wunsch, 1955; Hickey, 1975; Wyrtki, 1973, 1980, 1985; Rebert

et al., 1985, to name a few). These relations are generally established from given datasets and, due to the paucity of long time series measurements, rarely applied to independent datasets in order to test their abilities to improve the knowledge of heat content variations. A Pacific sea level monitoring network (K. Wyrtki; University of Hawaii) and the XBTs deployed since 1979 from merchant ships operating out of Noumea (New Caledonia) have now produced these required long time series measurements and allow such testing. This is the goal of this paper in which the statistical relationships between heat content and sea level are obtained through an original method consisting of using steric level as a surrogate variable for the sea level.

The data and data processing are presented in section 2a–b. Sea level and steric level obtained from climatological data are compared for 16 tropical Pacific locations in order to examine whether one parameter can be used as a surrogate for the other [section 2b(1)]. Statistical relationships between the averaged temperature of the upper 300 meters ($\bar{T}$) and the steric level (ST) used as a surrogate for the sea level (SL) are then derived from calculated data in Section 2b(2). These relationships are used with sea level measurements re-

corded during the 1979–85 period as input in order to hindcast $\bar{T}$, which is then compared to $\bar{T}$(XBT), computed from XBT profiles (section 3).

Note that heat content and T will be employed interchangeably in the text since they are·directly proportional through the product of density and heat capacity (C_p) of sea water and the 300 meters depth.

2. Data and methods

a. The data

The basic data used for this study can be separated into three categories. The first one is the seasonal climatological mean temperature and salinity profiles, $T(z)$ and $S(z)$, obtained in each 1° square of the tropical Pacific Ocean. These profiles, available from the National Oceanographic Data Center (NODC), are parts of those computed by Levitus (1982) for the world ocean. From a given temperature profile $T(z)$, variations of $\bar{T}$, denoted at $\bar{T}$(C1) when calculated from climatological data, are given by

$$\bar{T}(C1) = 1/300 \int_0^{300} [T(z) - \langle T(z) \rangle] dz$$

where $T(z)$ and $\langle T(z) \rangle$ are respectively the 3-month averaged and annual mean temperature profiles. Similarly, from a given density profile $\rho(z)$, variations of ST(C1), as defined by Gill and Niiler (1972), are calculated from

$$ST(C1) = -\frac{1}{\rho_0} \int_0^{300} [\rho(z) - \langle \rho(z) \rangle] dz$$

where $\rho(z)$ and $\langle \rho(z) \rangle$ are respectively the 3-month averaged and annual mean density profiles.

The second dataset is composed of the climatological monthly means of sea level SL(C1) recorded in different locations of the tropical Pacific Ocean (Wyrtki and Leslie, 1980). Sixteen locations for which we have long time records of sea level, i.e., more than ten years, were chosen for best future comparisons with steric level. These locations are presented in Fig. 1.

The third category of data is the XBTs temperature profiles and the sea surface salinity (SSS) measurements recorded in the 1979–85 period. The XBTs were collected along different trans-Pacific ship-of-opportunity routes (Fig. 1). This has been made possible by the development of a measurement system operated by the ORSTOM/SIO volunteer observing ship XBTs program (Meyers and Donguy, 1980). Additional XBT observations have been obtained from a variety of other sources (e.g., French Navy, FNOC, Japan Oceanographic Data Center, NODC). Parts of these XBT profiles will be used here to monitor $\bar{T}$, denoted as $\bar{T}$(XBT), at the following locations:

Christmas Island (1°57'N, 157°28'W)

Fanning Island (3°52'N, 159°22'W)

Truk Island (7°27'N, 151°51'E)

where sea level was measured and provided to us in the form of monthly means. An objective–subjective criterion based on multiples of the standard deviations was used to detect XBTs of dubious quality which were then plotted and visually compared to the local climatology for the 1979–85 period and to mean seasonal temperature profiles as computed by Levitus (1982). Approximately 2.5% of the total XBTs were rejected and 2% corrected.

b. Statistical analysis

1) COMPARING SEA LEVEL AND STERIC LEVEL

According to Gill and Niiler (1972), the changes in the sea level at one point can be expressed as the sum of three terms: 1) the steric level representing the effect of expansion or contraction of the water column, 2) the barometric term dependent on the surface atmospheric pressure variations and, 3) a term which is proportional to changes in bottom pressure. On a seasonal time scale and over a tropical ocean, it has been shown that the last two terms are negligible and that steric level and sea level changes agree relatively well (Patullo
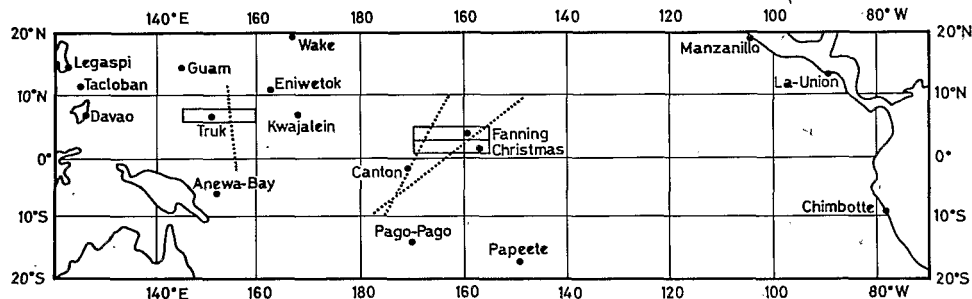

FIG. 1. The black dots denote the locations of long term sea level records where comparisons between steric level and sea level were performed. The shipping routes with available XBT measurements, crossing the 2° latitude × 15° longitude rectangles are shown.

et al., 1955; Wunsch, 1972; Gill and Niiler, 1972). We verify this assumption in our area of interest by comparing variations of ST(C1) and SL(C1) in the vicinity of locations where sea level was measured. To this end, 3-month averaged variations (i.e., 3-month averaged minus annual mean) of ST(C1) have been calculated for the nine closest 1° squares surrounding each of the 16 locations with long term sea level measurements. The standard deviations of ST(C1), relative to the average over these 1° squares, are used to represent the errors, and range between 15% and 25% of the means. Three-month averaged variations of SL(C1) were derived from monthly sea level values and their accuracy is assumed to be 2 cm (Rossiter, 1963; Wyrtki, 1973).

The comparisons between variations in ST(C1) and SL(C1) are presented in Fig. 2 for the 16 locations. The results thus obtained indicate a good correspondence between the two quantities. A significant (95% level) correlation, $R = 0.74$, was found, the rms difference is 2.5 cm, i.e., well within the error bars of both mea-

surements. This result is used in section 3 where it will thus be assumed that sea level changes are representative of steric level changes.

2) RELATIONSHIP BETWEEN $\bar{T}$ AND STERIC LEVEL

Three-month averaged variations in ST(C1) and $\bar{T}$(C1) are now related by means of a linear regression analysis in order to be able to deduce $\bar{T}$ from sea level assumed to be well represented by the steric level. Regional relationships were established, from climatological data, in the three 2° in latitude by 15° in longitude rectangles surrounding Fanning, Christmas and Truk Islands (Fig. 1). The size and geographical locations of these rectangles were chosen in order to have a sufficient number ($15 \times 2 \times 4$) of available calculated values in $\bar{T}$(C1) and ST(C1) for the comparison, and to select an adequate number of XBT profiles for the computation of $\bar{T}$(XBT) in section 4. The scatter plots of ST(C1) versus $\bar{T}$(C1) and the correlations and slopes
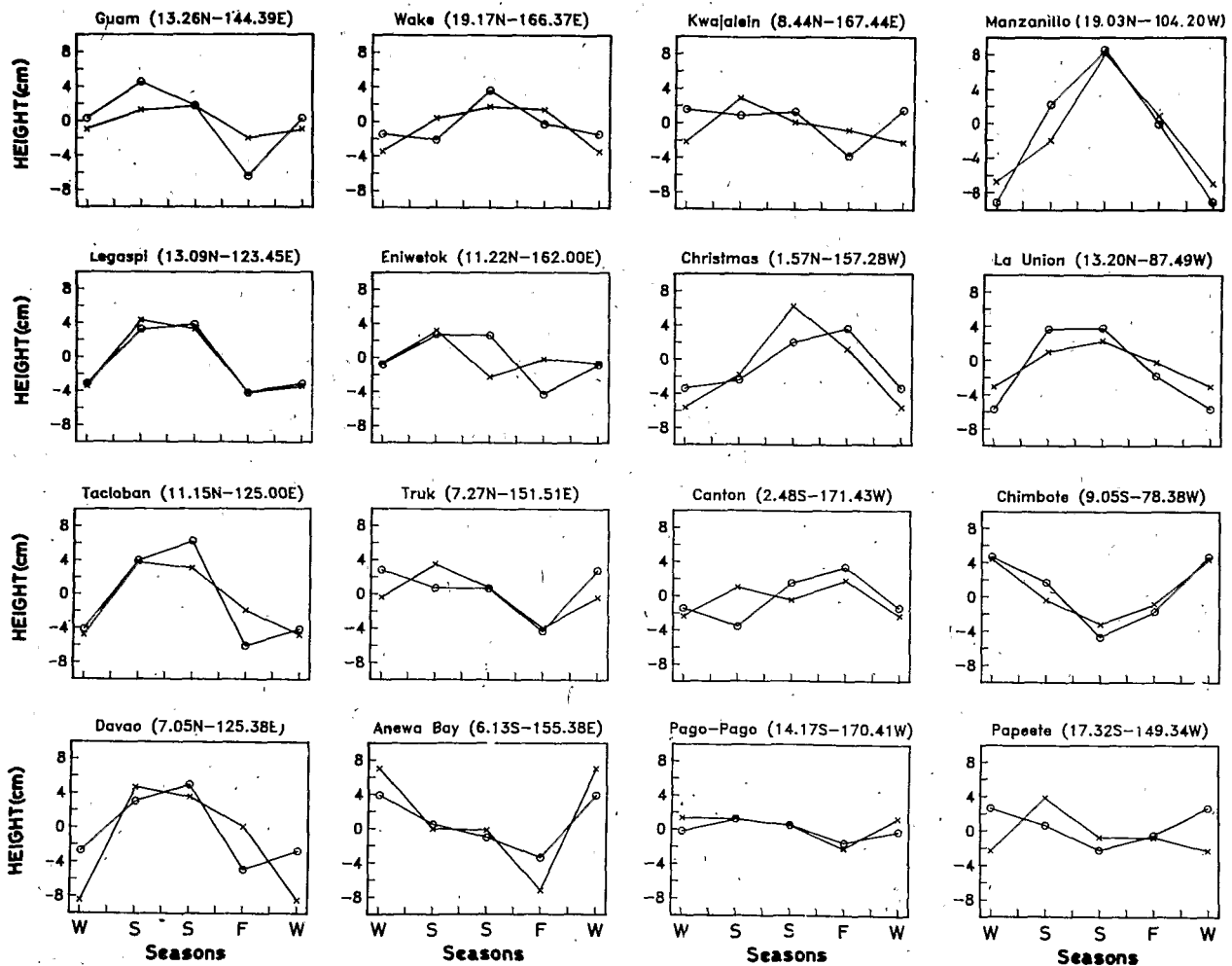

FIG. 2. Comparison between the seasonal steric level (ST(C1):X) and sea level (SL:0) variations 16 locations of the tropical Pacific Ocean. The errors in the sea level are 2 cm and those in the steric level about 25% of the seasonal signals. Winter (W) = Feb–Apr, etc.
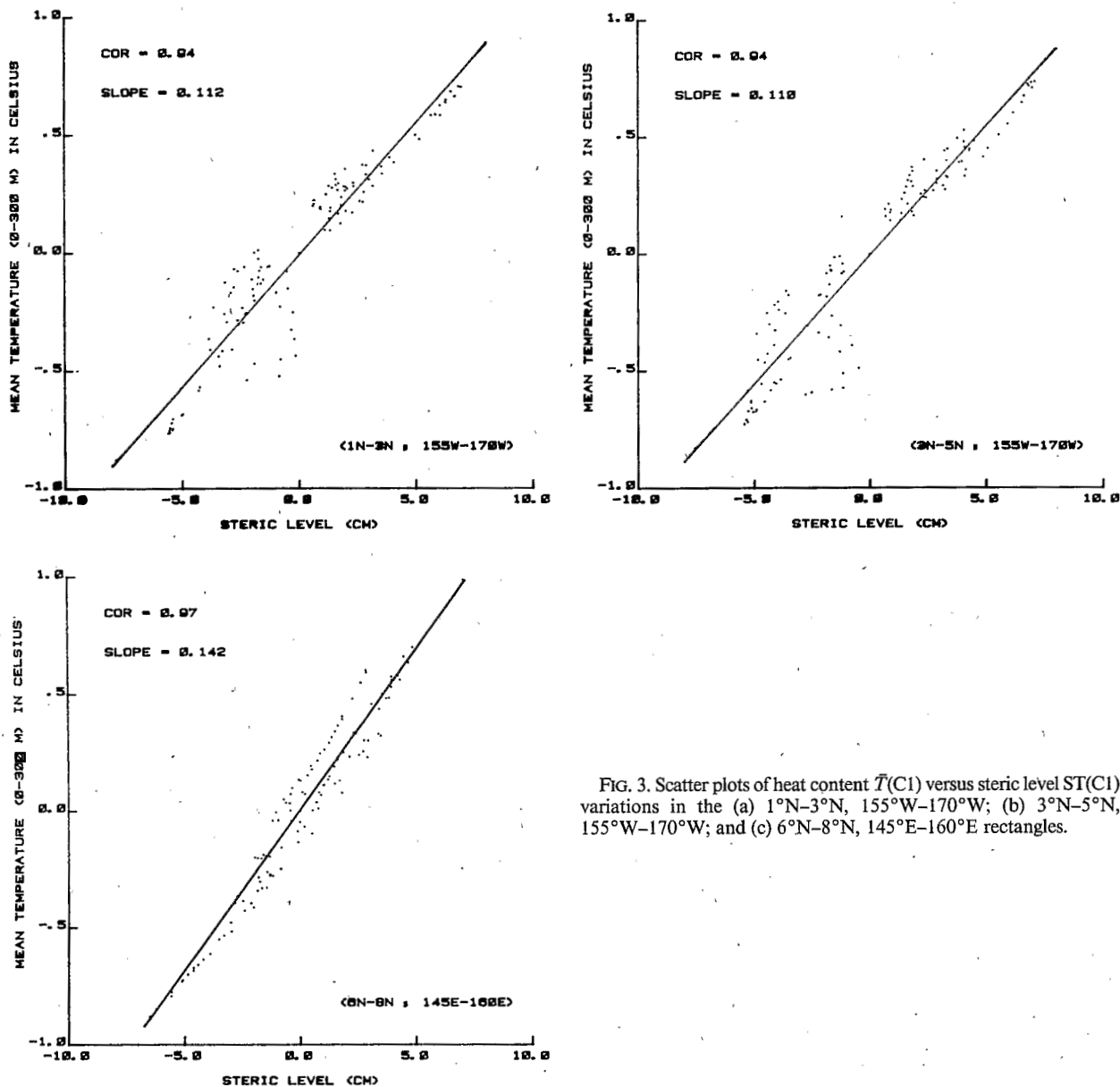
FIG. 3. Scatter plots of heat content $\bar{T}(C1)$ versus steric level ST(C1) variations in the (a) 1°N–3°N, 155°W–170°W; (b) 3°N–5°N, 155°W–170°W; and (c) 6°N–8°N, 145°E–160°E rectangles.

of their regression lines are shown in Figs. 3a–3c for each rectangle. In Figs. 3a and 3b, no simple explanation was found to account for the observed bimodal character of the data distribution. The good correlations between the two compared quantities could be expected since they were calculated with the same temperature profiles. On each rectangle, different relations between ST(C1) and $\bar{T}(C1)$ have been found. In fact, changes in steric level result from variations in temperature and salinity profiles, whereas changes in heat content are only due to changes in the temperature profile. These relations are thus dependent on the local salinity contributions to the steric level. In the vicinity of Truk Island, a large salinity variability exists from the surface down to 200 m, whereas in the vicinity of Christmas and Fanning Islands, salinity does not have the same high level of variability (Emery and Dewar, 1982, Figs. 12g and 12h). Relative influences of salinity to the steric level are thus notably different and induce specific relations between $\bar{T}(C1)$ and ST(C1). Moreover, relations between ST(C1) and $\bar{T}(C1)$ are dependent upon the shape of the mean TS curves. Looking in the TS plan, whether the large temperature variations occur where the partial derivative $\delta T/\delta S$ is negative/positive, salinity and temperature influence the density in the same/opposite sense and thus maximize/minimize steric level variations. In the investigated areas, this effect was difficult to quantify, since the largest temperature varia-

tions occur in the depth range of the main thermocline (75 to 150 m) i.e., astride on $\delta T/\delta S$ positive and negative.

3. Results

The XBT launch inside the $2° \times 15°$ rectangles surrounding Fanning, Christmas and Truk Islands are used to compute 1-, 2- and 3-month averaged XBT heat content estimates [$\bar{T}$(XBT)]. Variations in $\bar{T}$(XBT) are first described and the statistical relationships between $\bar{T}$(C1) and ST(C1) previously derived are then used to test whether these variations could have been estimated from sea level measurements recorded at these islands.

a. Variations in $\bar{T}$(XBT)

Three- and two-month averaged variations in $\bar{T}$(XBT) are presented in Figs. 4a–c and 5a–c (solid lines). Three-month averaged variations are only described here because the comments would have been very similar to the 3-month averaged variations. In the remaining text, we will use the term heat content for the average temperature over 300 m and therefore discuss its variability using units of degree Centigrade.

The pre-El Niño period is considered first (Jan 79– Jun 82). In both the central Pacific rectangles, the major signal, which is more visible in Fig. 4b, is the significant annual component of variability with an amplitude of about 0.75°C, the minimum heat content value occurring in May–June of each year. The mean heat content values were roughly 19°C in the 1°–3°N by 155°– 170°W rectangle, and its variability slightly larger than +0.25°C away from the equatorial upwelling in the 3°–5°N by 155°–170°W rectangle. In the western Pacific rectangle (Fig. 4c), the annual cycle is difficult to evaluate considering the missing XBT measurements in 1979 and 1981. However, the 1980 seasonal cycle seems dominated by a 2-cycle per year component in phase with those derived by Meyers (1982, Fig. 4) for the climatological sea level signal. The effects of El Niño (1982–83) were quite remarkable in both areas. A rapid $\bar{T}$ decrease (19°C to 15.75°C) which started in early 1982 is seen in the vicinity of Truk Island (Fig. 4c) until the end of 1982. A similar decrease happens about eight months later in the central Pacific (Figs. 4a and 4b), preceeded in the 1°–3°N by 155°–170°W rectangle (Fig. 4a) by an accumulation of warm water (21°C) at the end of 1982. The annual cycle observed in the pre-El Niño period is still detectable in the northern central Pacific rectangle (Fig. 4b), modulating the rapid variations in the heat content until the middle of 1985. Finally, the heat content is increasing back to "normal" in about six months in the western rectangle (Fig. 4c), whereas it took more than two years in the central Pacific (Figs. 4a and 4b). The timing and duration of El Niño will thus be defined differently in the investigated areas, i.e., from June 1982 to June 1983
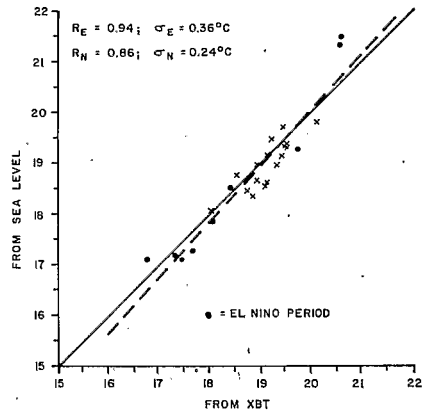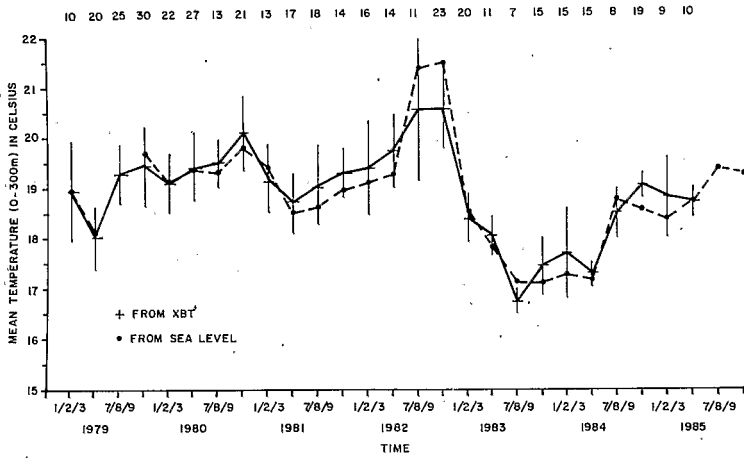
in the western rectangle and June 1982 to June 1984 in the central ones.

b. Variations in $\bar{T}$(SL) and comparisons with $\bar{T}$(XBT)

Whether variations in $\bar{T}$(XBT) over the 1979–85 period could have been predicted from sea level measurements recorded in Christmas, Fanning and Truk Islands is now investigated. To this end, monthly sea level measurements recorded at these islands are averaged over 1-, 2- and 3-month periods to deduce variations in $\bar{T}$(SL) using the relations previously determined between ST(C1) and $\bar{T}$(C1) over a climatological mean. Note that these relations were established on 3-month averaged variations and are thus extrapolated to 1- and 2-month averaged variations in order to test their predictive ability on shorter periods. The minimum resolution in $\bar{T}$(SL) is linked to the 2 cm uncertainty in sea level, i.e., 0.23°C, 0.22°C and 0.29°C for Christmas, Fanning and Truk Islands, respectively. The standard deviation of $\bar{T}$(XBT) relative to the averaged period has simply been taken as a rough estimate of the error.

Comparisons between 3- and 2-month averaged estimates in $\bar{T}$(XBT) and $\bar{T}$(SL) are presented in Figs. 4a–4c and 5a–5c. They show very good qualitative agreement for each rectangle, considering that sea level is recorded continuously at a fixed station whereas the XBT profiles are spot measurements at a location which can be several hundred kilometers away from the sea level station. Significant correlations (95% level) $R = 0.78$ to 0.94 and rms differences of 0.25 to 0.50°C (see Table 1) over an observed $\bar{T}$(XBT) range of 6°C were found between the two compared quantities, respectively including and excluding the major El Niño event mentioned previously. On 2- and 3-month averaged periods, 61% to 88% of the variance in $\bar{T}$(XBT) can thus be deduced from sea level measurements only. The mean differences between 2- (3-) month averaged heat content estimated from XBT and sea level [$\bar{T}$(XBT) − $\bar{T}$(SL)] were 0.07°C (0.07), −0.15°C (0.22) and 0.05°C (0.11) for rectangles surrounding Christmas, Fanning and Truk Islands, indicating a slight bias due to the time averaged period in the vicinity of Fanning Island. The worst correspondence (not presented here) between the two compared quantities occurs when averaging over a one-month period (see Table 1). Whether this is due to the smaller XBT sample sizes or to differences in the physical processes occurring over this time scale cannot be deduced without a local systematic experiment over the entire time domain. The two independent measures $\bar{T}$(XBT) and $\bar{T}$(SL) quantitatively agree within their given error limits in both rectangles except at the end of 1982 (i.e., Figs. 4a and 4b), around Christmas and Fanning Islands. This was a period of intense rainfall and unusually low sea surface salinity (Donguy and Eldin, 1985; Sadler and Kilonski, 1985).
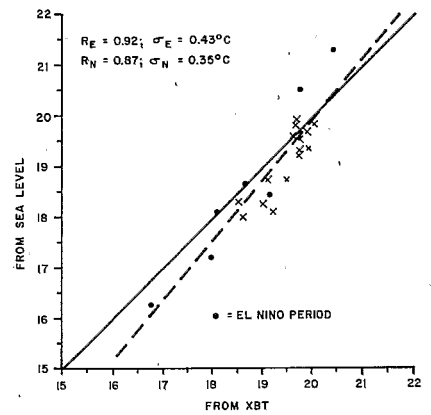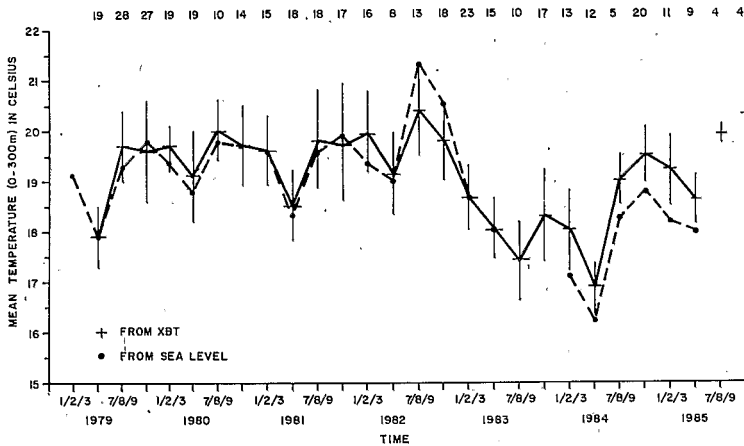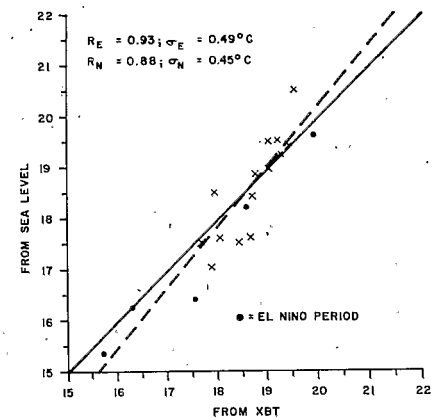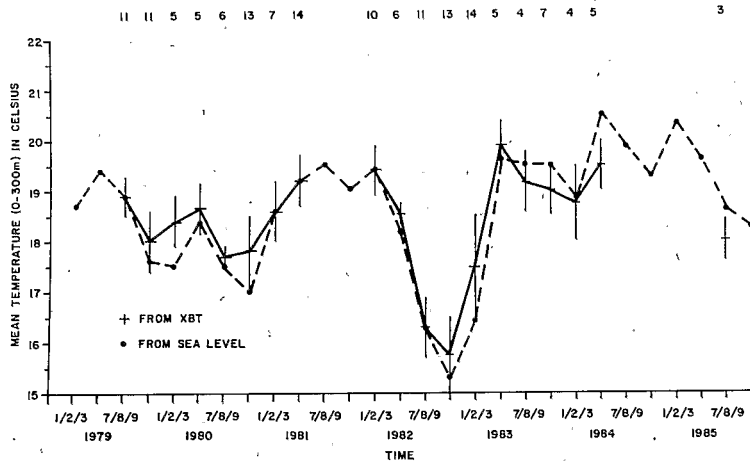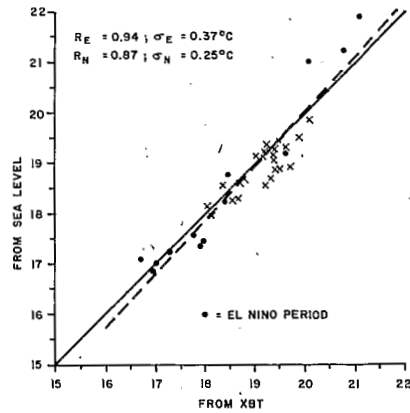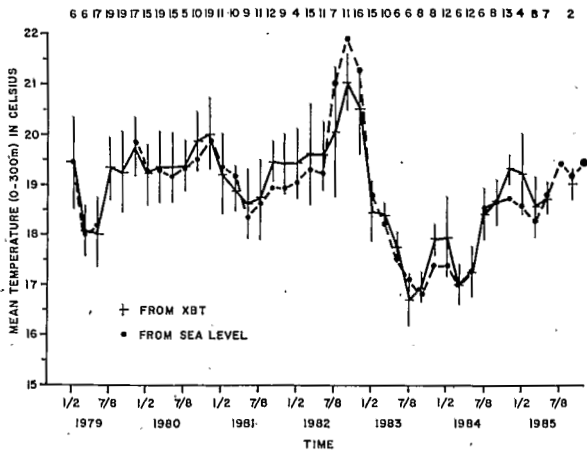
·FIG. 4a. (left panel) Comparison between 3-month-averaged XBT heat content estimates $\bar{T}$(XBT) in the (1°N–3°N, 155°W–170°W) rectangles (solid lines) and the heat content derived from sea level recorded in Christmas Island $\bar{T}$(SL) (broken lines). The bars denote the standard deviations of $\bar{T}$(XBT) during the given period. The upper numbers are the numbers of XBT profiles used to calculate the heat content. (right panel) Regression analysis between the two heat content estimates $\bar{T}$(XBT) and $\bar{T}$(SL). R_e, rms$_e$ (σ_e) and R_n, rms$_n$ (σ_n) are defined in Table 1.
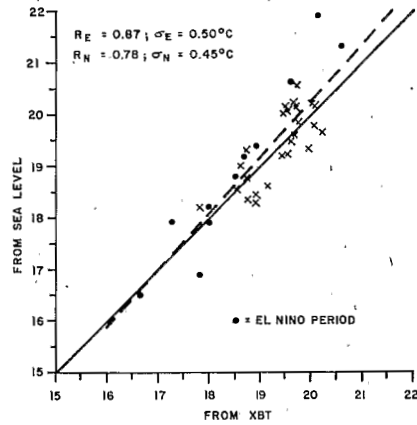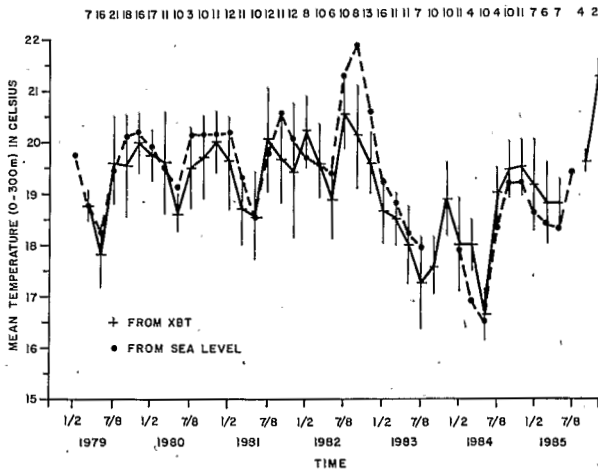
FIG. 4b. (left panel) Comparison between 3-month-averaged XBT heat content estimates $\bar{T}$(XBT) in the (3°N–5°N, 155°W–170°W) rectangles (solid lines) and the heat content derived from sea level recorded in Fanning Island $\bar{T}$(SL) (broken lines). The bars denote the standard deviations of $\bar{T}$(XBT) during the given period. The upper numbers are the numbers of XBT profiles used to calculate the heat content. (right panel) Regression analysis between the two heat content estimates $\bar{T}$(XBT) and $\bar{T}$(SL). R_e, rms$_e$ (σ_e) and R_n, rms$_n$ (σ_n) are defined in Table 1.

FIG. 4c. (left panel) Comparison between 3-month-averaged XBT heat content estimates $\bar{T}$(XBT) in the (6°N–8°N, 145°W–160°W) rectangles (solid lines) and the heat content derived from sea level recorded in Truk Island $\bar{T}$(SL) (broken lines). The bars denote the standard deviations of $\bar{T}$(XBT) during the given period. The upper numbers are the numbers of XBT profiles used to calculate the heat content. (right panel) Regression analysis between the two heat content estimates $\bar{T}$(XBT) and $\bar{T}$(SL). R_e, rms$_e$ (σ_e) and R_n, rms$_n$ (σ_n) are defined in Table 1.

FIG. 5a. (left panel) Comparison between 2-month-averaged XBT heat content estimates $\bar{T}$(XBT) in the (1°N–3°N, 155°W–170°W) rectangles (solid lines) and the heat content derived from sea level recorded in Christmas Island $\bar{T}$(SL) (broken lines). The bars denote the standard deviations of $\bar{T}$(XBT) during the given period. The upper numbers are the numbers of XBT profiles used to calculate the heat content. (right panel) Regression analysis between the two heat content estimates $\bar{T}$(XBT) and $\bar{T}$(SL). R_e, rms$_e$ (σ_e) and R_n, rms$_n$ (σ_n) are defined in Table 1.
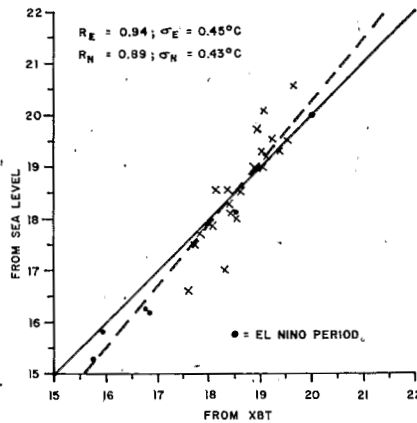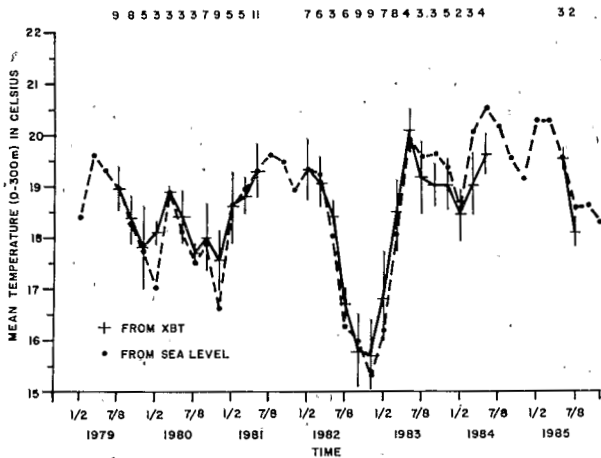
FIG. 5b. (left panel) Comparison between 2-month-averaged XBT heat content estimates $\bar{T}$(XBT) in the (3°N–5°N, 155°W–170°W) rectangles (solid lines) and the heat content derived from sea level recorded in Fanning Island $\bar{T}$(SL) (broken lines). The bars denote the standard deviations of $\bar{T}$(XBT) during the given period. The upper numbers are the numbers of XBT profiles used to calculate the heat content. (right panel) Regression analysis between the two heat content estimates $\bar{T}$(XBT) and $\bar{T}$(SL). R_e, rms$_e$ (σ_e) and R_n, rms$_n$ (σ_n) are defined in Table 1.

FIG. 5c. (left panel) Comparison between 2-month-averaged XBT heat content estimates $\bar{T}$(XBT) in the (6°N–8°N, 145°W–160°W) rectangles (solid lines) and the heat content derived from sea level recorded in Truk Island $\bar{T}$(SL) (broken lines). The bars denote the standard deviations of $\bar{T}$(XBT) during the given period. The upper numbers are the numbers of XBT profiles used to calculate the heat content. (right panel) Regression analysis between the two heat content estimates $\bar{T}$(XBT) and $\bar{T}$(SL). R_e, rms$_e$ (σ_e) and R_n, rms$_n$ (σ_n) are defined in Table 1.

TABLE 1. Correlation coefficients (R_e, R_n) and rms differences (rms$_e$, rms$_n$) between the heat content (mean temperature, 0–300 m) estimated from XBT and sea level for the given rectangles and averaged periods, including (e) or excluding (n) the El Niño event as defined in the text.

	1°N–3°N 155°W–170°W	3°N–5°N 155°W–170°W	6°N–8°N 145°E–160°E
1-month averaged	$R_e = 0.89$; rms$_e = 0.51°C$ $R_n = 0.74$; rms$_n = 0.36°C$	$R_e = 0.78$; rms$_e = 0.69°C$ $R_n = 0.62$; rms$_n = 0.56°C$	$R_e = 0.90$; rms$_e = 0.59°C$ $R_n = 0.82$; rms$_n = 0.57°C$
2-month averaged	$R_e = 0.94$; rms$_e = 0.37°C$ $R_n = 0.87$; rms$_n = 0.25°C$	$R_e = 0.87$; rms$_e = 0.50°C$ $R_n = 0.78$; rms$_n = 0.45°C$	$R_e = 0.94$; rms$_e = 0.45°C$ $R_n = 0.89$; rms$_n = 0.43°C$
3-month averaged	$R_e = 0.94$; rms$_e = 0.36°C$ $R_n = 0.86$; rms$_n = 0.24°C$	$R_e = 0.92$; rms$_e = 0.43°C$ $R_n = 0.87$; rms$_n = 0.35°C$	$R_e = 0.93$; rms$_e = 0.49°C$ $R_n = 0.88$; rms$_n = 0.45°C$

Figure 6 shows the sea surface salinity (SSS) variations in the investigated rectangles over the 1979–85 period, provided by the ship-of-opportunity network operating off Noumea since 1969. About 3.7 observations per month and rectangle were available. The SSS exhibits a large variability all over the 1979–85 period (rms = 0.45‰) around Truk Island; the El Niño effect being possibly characterized by a rapid SSS increase (+1‰) similar to those occurring in mid-1980. On the other hand, in the vicinity of Christmas and Fanning Islands the SSS variability was low prior to El Niño with peak-to-peak variations less than 0.4‰ and rms of 0.2‰. Even if the SSS represents the salinity of the entire shallow mixed layer, the local effect of this variability on the steric level (thus in the sea level) would be about 1 cm, which is only half of the uncertainty in monthly sea level measurements. During the

El Niño event, on the other hand, SSS fell rapidly in July–August 1982 (−1‰) and remained low for half a year, recovering gradually by mid-1983. Assuming that such a variation occurs over a 60 m depth (which is consistent with the single R/V *Discoverer* CTD cast made in April 1983 at 0°–155°W), this could produce a significant 6 cm increase in the steric level and a deduced 0.66°C variation in $\bar{T}$(SL) only resulting from the salinity variability. If this last value is subtracted from $\bar{T}$(SL) on Figs. 4a and 4b (and 5a and 5b) during the El Niño event, differences between the two $\bar{T}$ estimates then become comparable to the previous differences and within the noise of both estimates. This suggests that the vertical salinity structure variability, rarely available, could be used to improve estimates of $\bar{T}$(SL) relative to $\bar{T}$(XBT). In a recent paper, Kessler and Taft (1986) have shown that, in the central Pacific,
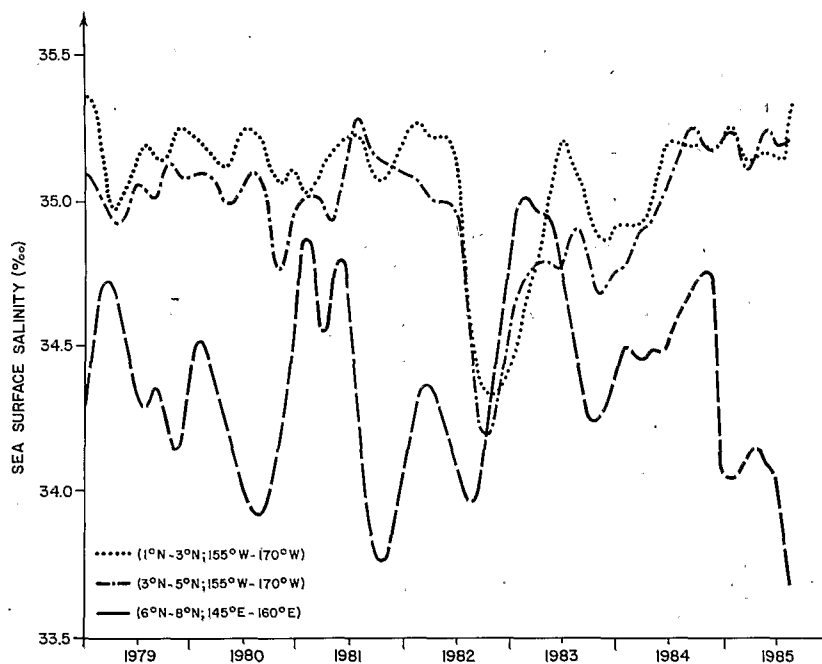

FIG. 6. Sea surface salinity variations in the reported rectangles during the 1979–85 period.

this vertical structure variability can be fairly well deduced by means of temperature profiles and SSS ("Linear TS scheme"). However, the goal of our paper was to estimate $\bar{T}$ through sea level data only and thus we assume that no oceanic vertical measurements are available. Sea surface salinity (SSS) variations and differences in the $\bar{T}$ estimates $[\bar{T}(\text{XBT}) - \bar{T}(\text{SL})]$ were thus compared and a significant (95% level) correlation $R = 0.54$ has been found in the central Pacific rectangles ($R = 0.17$ was not significant in the western Pacific). In conclusion, SSS variability in the central Pacific is a possible indicator of the reliability of using sea level to derive $\bar{T}$. The knowledge of the SSS thus permits to a priori improve $\bar{T}$ estimated from sea level measurements, but independent datasets of sea level, XBT and SSS, not presently available, would be suitable to test such a possibility.

4. Summary and conclusions

The goal of this paper was to test the possibility of using sea level measurements recorded in Christmas, Fanning and Truk Islands to determine 1-, 2- and 3-month averaged variations in the mean temperature of the upper 300 m ($\bar{T}$), in spatial boxes (2° latitude × 15° longitude) surrounding these islands. To this end, the good correspondence between steric level and sea level variations already reported by many investigators was verified in the vicinity of 16 tropical Pacific islands over a mean seasonal time scale. This result was extrapolated to our areas of interest in order to use the steric level as a surrogate variable for the sea level. Regional linear parameterizations between heat content [$\bar{T}$(C1)] and steric level [ST(C1)] variations were then established, from climatological data, on each 2° × 15° box referenced above. In the 1979–85 period, XBT heat content estimates [$\bar{T}$(XBT)] were then compared with heat content derived from island sea level measurements [$\bar{T}$(SL)] using the linear parameterizations between $\bar{T}$(C1) and ST(C1). For 2- and 3-month averaged variations, good qualitative agreement was found between the two estimates, including or excluding the 1982–83 El Niño event (correlations $R = 0.78$ to 0.94 and rms differences of 0.25° to 0.50°C over an observed range of variations of 6°C). Observed quantitative disagreements were always within the error bars of the two compared quantities except during the fall 1982 period in the central Pacific. At this time, intense rainfall and very unusually low SSS were observed in the area, and the quantitative disagreement results from notable salinity contributions to the sea level. In fact, a significant correlation $R = 0.54$ has been found between SSS and the differences between the $\bar{T}$ estimates. Sea surface salinity is thus a good indicator of the reliability of using sea level to derive $\bar{T}$ and would probably permit a correction in the sea level signal due to large salinity profile variations. Satellite-derived precipitation estimates might offer another alternative to

perform the salinity correction. Although the presented results are local and thus should be generalized to other locations only with great caution, they are encouraging for using future altimetry sea surface topography data to derive heat content variations. Such a possibility, which still needs to be demonstrated, would provide essential initial data to forecast an El Niño event (Wyrtki, 1985; Cane et al., 1986). In this framework, some limitations would be brought by: 1) the accuracy of satellite sea level measurements and, 2) the possibility of quantifying and correcting sea level changes due to intense and unusual SSS variations.

The accuracy of a sea level signal obtained from altimetry has already been discussed by many authors, the main point being to remove the largest errors due to the geoid by means of crossing arcs or repeat orbit data (Cheney and Marsh, 1981). A given monitored spatial box should be large enough to ensure a large number of crossing arcs in the area, but small compared with the local scale of oceanic variability so that the computed average sea level is a meaningful quantity. Some estimates of box size might be derived from observed space–time covariance and we can expect methods to be developed to massage the raw data adequately in order to account for small signals over a time scale of 2–3 months. The second limitation of the proposed approach is the need for correction of the sea level variations due to large SSS contributions. As noted before, these corrections are really necessary when intense and unusual SSS variations occur. Information about the amplitude of these variations could be provided through continuous monitoring of SSS variability as detected by existing ship-of-opportunity programs combined with available historical SSS data. A good satellite-derived tropical precipitation dataset would also be useful for this correction.

It would be suitable to validate this method in different parts of the tropical Pacific ocean and especially to test, on independent datasets, whether the intense and unusual SSS variations can be used as an indicator of the reliability of using sea level to derive heat content. It is thus expected that future altimetry sea level measurements combined with SSS, XBT and satellite-derived precipitation estimates will give us the necessary datasets to explore such possibilities in the open Pacific ocean.

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