Vertical Thermal Structure Variability along 165°E During the 1986-87 ENSO Event.

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ABSTRACT

Modifications of the intertropical thermal structure along the 165°E meridian linked to the 1986-87 ENSO are described and analyzed from results of a series of cruises carried out by ORSTOM from Nouméa, and additional data from the US-PRC Western Pacific program cruises.

During the evolution of the ENSO event, changes in the vertical distribution of temperature are found to be restricted mostly to the upper 400m. Therefore, temperature anomalies and vertical displacements of isotherms can be computed in relation to a climatology deduced from XBT data available in the region.

Warming and deepening of surface layers are apparent before the onset of the ENSO event, more important in the southern hemisphere warm pool ; then, a cooling of thermocline layers appears close to the equator at the beginning of 1987. The corresponding equatorial shoaling of isotherms extends progressively poleward in both hemispheres to 10° of latitude, while reaching sub-thermocline layers. This anomalous temperature pattern persists until the first half of 1988. In June 1988 temperature anomalies have lowered or changed sign, returning to a configuration close to that observed prior to the onset of ENSO.

Dynamic height and heat content anomalies are shown to be correlated to large scale sea level anomalies from GEOSAT altimeter data. Differences emphasize the smoothing of structures by satellite measurements. Mechanisms for large scale evolutions away from the equator are searched for in the effects of local wind stress forcing.

1. Introduction.

In the western tropical Pacific, a large part of the oceanic variability associated to ENSO events is generated through heat accumulation and release, and forcing of equatorial trapped waves (Wyrtki, 1985, Busalacchi and O'Brien, 1981). Because of high surface temperatures, strong ocean-atmosphere energy transfers occur there, particularly in the region of SST > 28°C known as the Warm Pool. Effects of atmospheric forcing are most important in the surface layer, by affecting surface mixing, sea level and thermocline depth, while variability is weaker below the thermocline. In this surface layer, above 400m, availability of XBT temperature measurements for a long time permits us to compare between ENSO and non-ENSO periods.

To better understand the variability of the zonal circulation system and thermohaline structure of the western tropical Pacific, a series of semi-annual cruises has been undertaken since 1984 along 165°E (ORSTOM's SURTROPAC program). Other research programs have since begun and are still carried out in the region, mainly the US-PRC cooperative program. A general description of the hydrology from historical cruises and for the 1984-86 period has been done previously (Delcroix *et al*, 1987, Toole *et al*, 1988).

The purpose of this paper is to use results from these cruises carried out from 1986 to mid-1988 to study how the occurrence of the 1986-87 ENSO event affected thermal structure and heat storage.

From November 1986-November 1987 are also available sea-level anomaly data from the GEOSAT Exact Repeat Mission (ERM), which are directly related to 'real' sea level and dynamic heights. We will then examine how much of the thermal variability observed during these cruises is reflected in satellite altimeter data.

From monthly wind stress data produced by the Florida State University (FSU) analysis, local contributions of wind forcing to the variability will be estimated.

2. Data.

Data gathered during 11 cruises are available to us at this time; Table 1 gives characteristics of these cruises. 10 are carried out along the 165°E meridian, but the Saga 02 cruise follows a different path, from 160°E to 170°E. Its results can still be used because of weak longitudinal variability. Best common coverage is obtained from 10°N-10°S, and emphasis will be put on this region.

Sections collected, 1986-88.

Cruise	Origin	Time	Section track
Surtropac 5	ORSTOM	10-26 January 1986	20°S-10°N.
Surtropac 6	ORSTOM	17-27 June 1986	20°S-10°N.
US-PRC 2	WHOI-SOA	8-16 December 1986	10°N-6°S at 165°E, then to 10°S at 160°E.
Surtropac 7	ORSTOM	10-27 January 1987	20°S-10°N.
Saga 2	SIO-IAG	23 May-6 June 1987	20°N-5°S at 160°E, then 10°S-19°S at 170°E.
Surtropac 8	ORSTOM	2-21 July 1987	20°S-10°N.
Proppac 1	ORSTOM	9-20 September 1987	20°S-6°N.
US-PRC 3	WHOI-SOA	13-22 October 1987	Same as for US-PRC 2.
Surtropac 9	ORSTOM	16-28 January 1988	20°S-10°N.
Proppac 2	ORSTOM	28 March-8 April 1988	20°S-6°N.
Surtropac 10	ORSTOM	14-27 June 1988	20°S-10°N.

TABLE 1. Detail of cruise tracks and dates. ORSTOM = Institut Français de Recherche Scientifique pour le Développement en Coopération, Nouméa, New Caledonia. WHOI = Woods Hole Oceanographic Institution, Woods Hole, MA, USA. SOA = State Oceanic Administration, Qingdao and Guangzhou, PRC. SIO = Scripps Institution of Oceanography, La Jolla, CA, USA. IAG = Institute of Applied Geophysics, Moscow, USSR.

All cruises have stations every degree of latitude, and every 1/2 degree close to the equator, excepted the Saga 02 cruise, where sampling is coarser. However, time sampling is very irregular; periods between cruises range from 1 to 6 months; fortunately, denser sampling is found at the peak and relaxation phases of the event, during the second half of 1987 and the beginning of 1988. Because of dense meridional sampling and coarse time sampling, it would be misleading to try to study these cruise results as time series at given latitudes, because time between cruises is often longer than time coherence of meridional structures.

Satellite sea-level anomaly data are filtered in time and space to remove noise and bad satellite tracks (Delcroix *et al*, this volume). This technique eliminates variability below 15 days and 1.5 degree of latitude. Only anomalies > l4cm (above rms accuracy) are kept as significant.

3. Climatology.

Anomalies of thermal structure are computed for each cruise from a monthly climatology obtained from XBT data for 1979-81 + 1984-85, in the 155°E-175°E region. Previous works (Hanawa and Yorikata, 1987, Hénin, personnal communication) have shown that differences in temperature data from XBT and CTD measurements are negligible; however, a difference of about 5% in depth measurements can be found. At the depth of the thermocline, this leads to an overestimation of isotherm depths of less than 10m in XBT data, which is small compared to observed displacements of the thermocline.

Figure 1 presents the climatological thermal structure seasonally averaged for December-February and June-August. Prominent features of this climatology are summarized below:

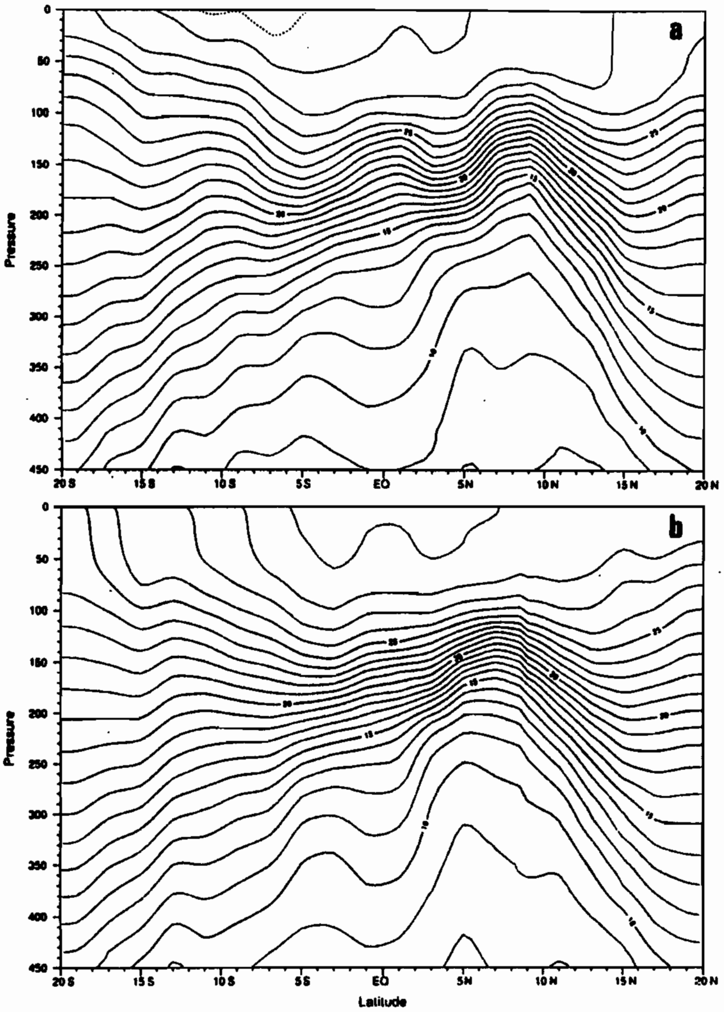


FIG. 1. Seasonal averages of temperature 0-400m, a) December-February (DJF) and b) June-August (JJA), from a monthly climatology obtained from XBT data 1979-81, 1984-85, in the 155°E-175°E region.

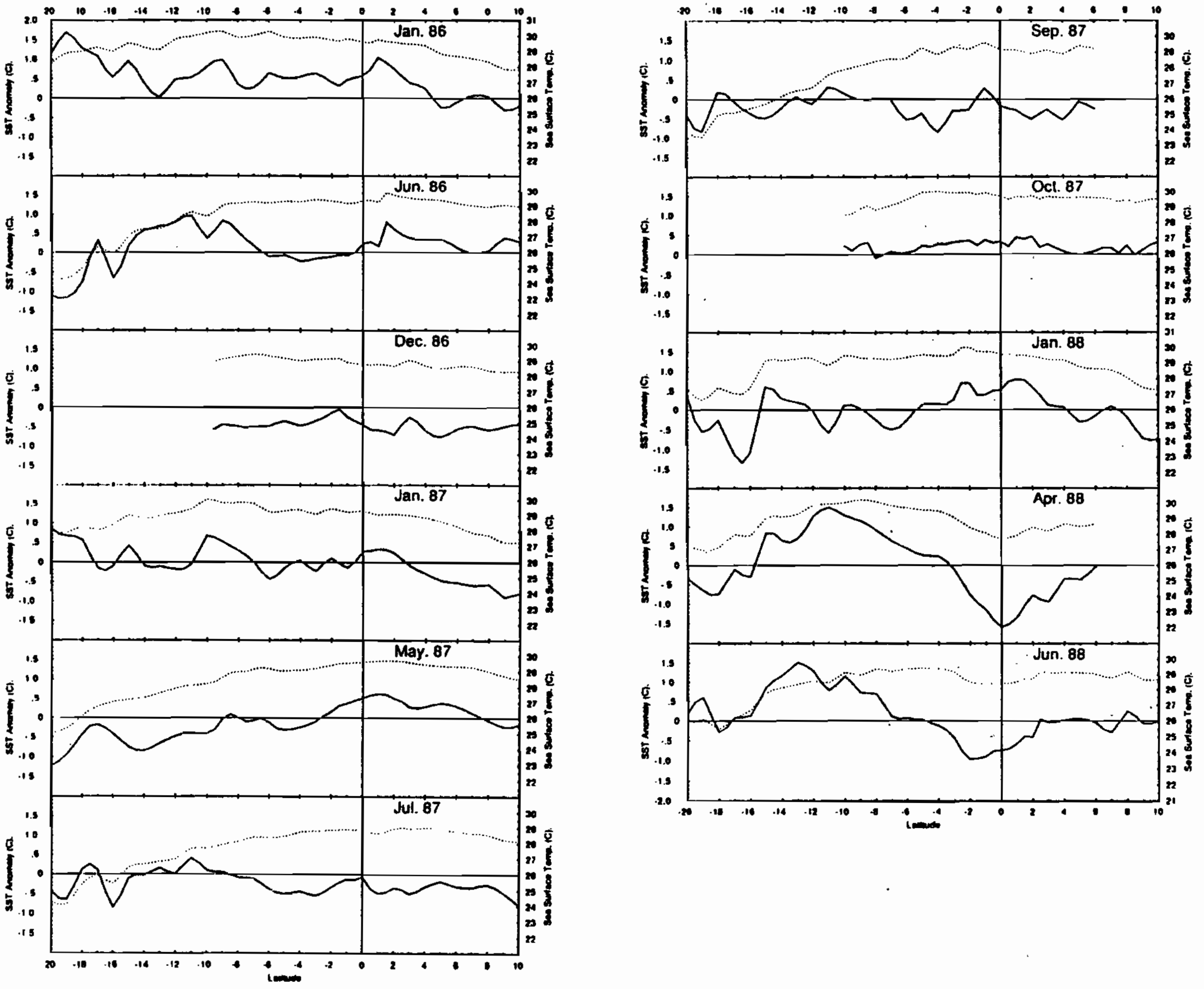


FIG. 2. SST and its anomaly for each of the 11 cruises as a function of latitude. SST: dotted lines, values on rightaxis. SST anomaly: solid lines, left axis.

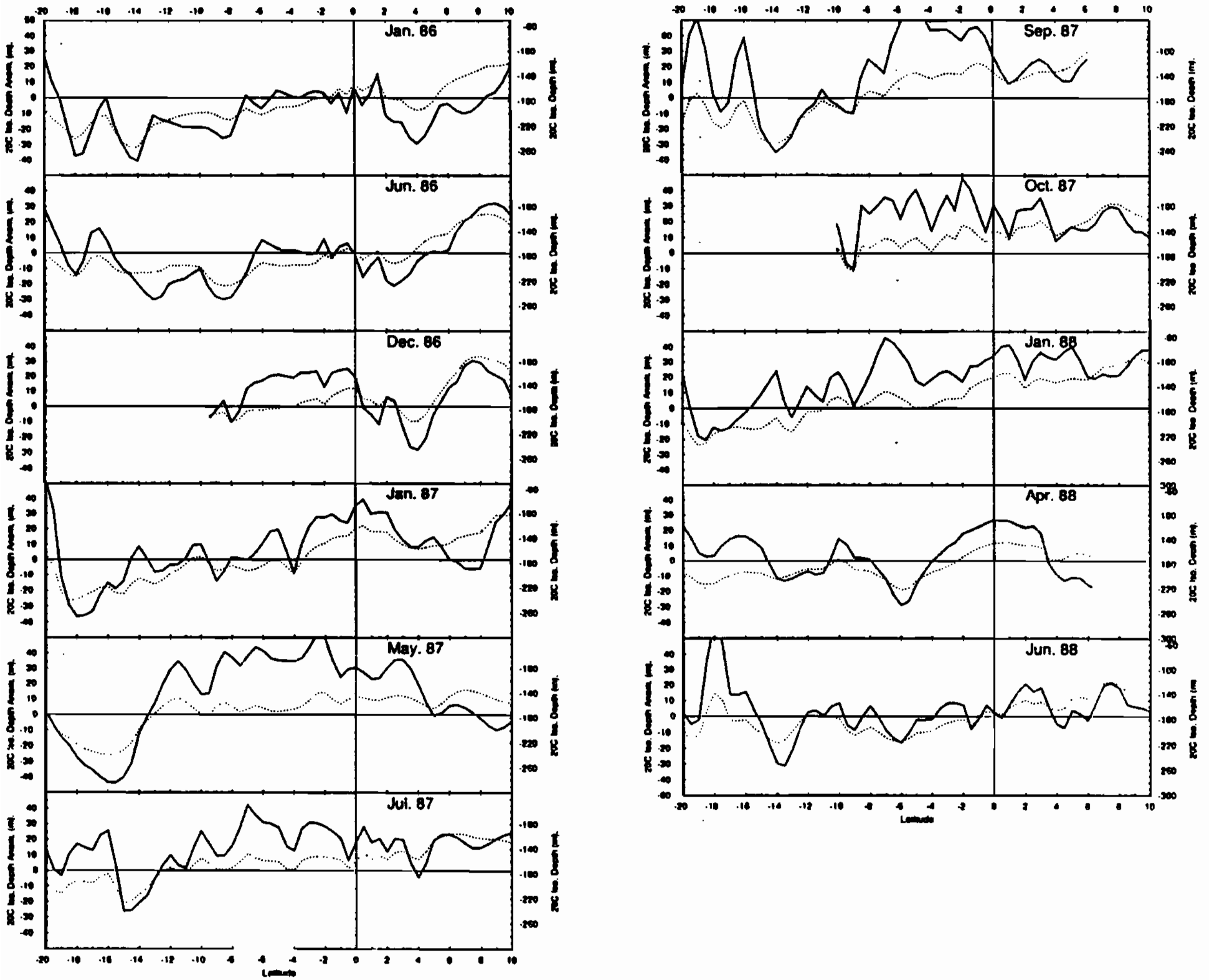
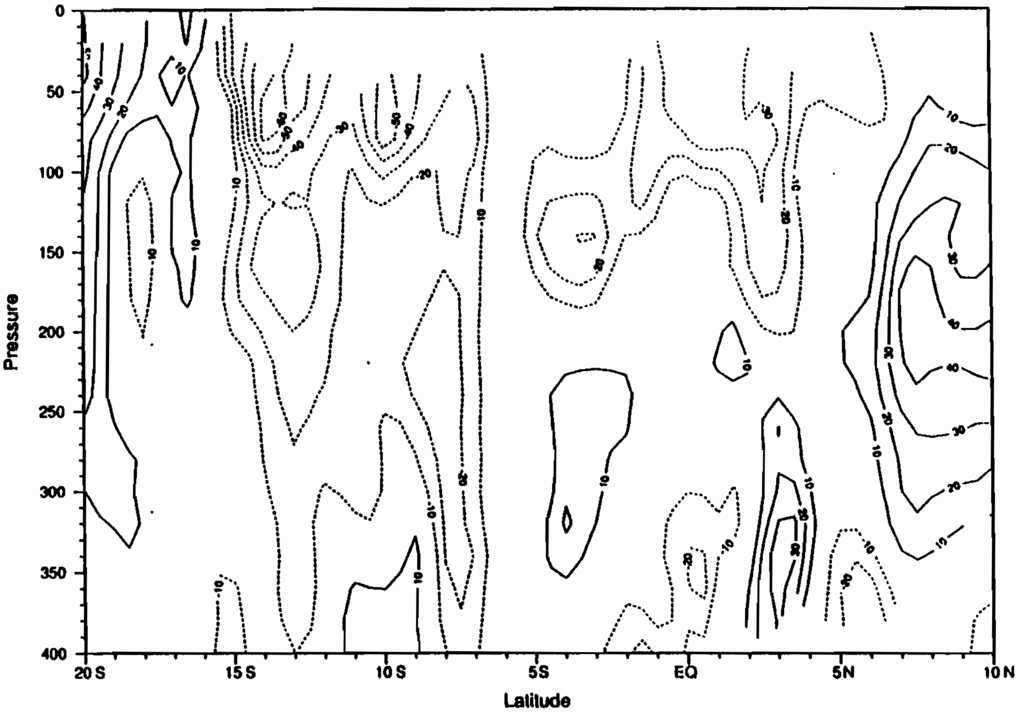


FIG. 3. Depth of the 20°C isotherm and its anomaly for each cruise. Isotherm depth: dotted line, right axis. Isotherm depth anomaly: solid line, left axis.

a. Surtropac06 Iso Depth Anomaly.



b. Surtropac08 Iso Depth Anomaly.

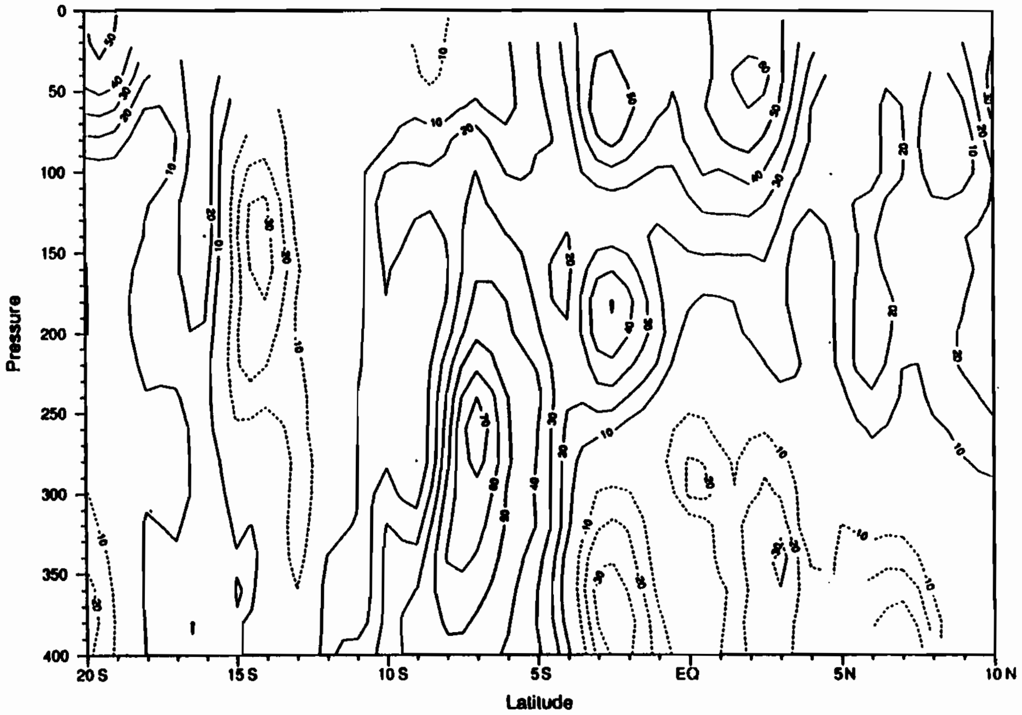


FIG. 4. Isotherm depths anomalies during a) the build-up and b) the peak phases of the 1986-87 ENSO. Anomalies at a given depth represent deviations of the corresponding isotherm depth from its monthly climatological value. Upward deviations positive, solid lines; downward deviations, dotted lines. Contouring interval is 10m.

-Weak seasonal variability of SST from 5°S-5°N, where SST stays above 29°C.

-Seasonal displacements of the warm pool, defined as the region where SST is above 28°C, which moves from 18°S-15°N to 10°S-20°N, following the summer hemisphere.

-Presence of a strong thermocline, centered around 20°C, with the ridges and troughs associated to geostrophic circulation in the 10°S-15°N band

-Weak seasonal variations below the 13°C isotherm.

4. Thermal structure evolution.

In the frame of this report, it is not possible to examine the complete 0-400 m structure for each cruise. Instead, three parameters are selected, as representatives of the upper water column:

-SST, which variability is weak, but which plays an important role in heat and moisture exchange.

-Depth of the 20°C isotherm, which is linked to the depth of the thermocline as shown by climatology.

-Heat content above 300m (HCo, given as 0-300m averaged temperature), which shows effects of combined local heating and advection.

a. SST.

Figure 2 presents the evolution of SST from January 1986-June 1988: SST anomalies stay weak, especially in the 10°S-10°N region, almost never exceeding 1°C. This explains that short term variability may hide evolutions from cruise to cruise. Noticeable are high temperatures found in January 1986 from 20°S-5°N; afterwards, the general trend is toward negative anomalies, reaching -1°C, especially north of the Equator during 1987, with exception of the Saga 02 cruise. After January 1988, SSTs climb, but this is obscured from 5°S-5°N by an unusual equatorial upwelling in April and June 1988.

b. Depth of 20°C Isotherm.

The evolution of the 20°C isotherm depth is presented on Figure 3: the three 1986 cruises show anomalous deepening (20-30m) of the thermocline from 15°S-8°S and 3N°-6°N, while the equatorial region stays close to normal. Also, an important increase in slope from 6°N-10°N corresponds to the increase in North Equatorial Countercurrent (NECC) transport already noted (Toole *et al*, 1988); this strong slope persists at the end of 1986, but the equatorial thermocline is now shoaled by 20m; in anomalies, this shoaling is enhanced because against seasonal variations. Shoaling increases again in 1987 to 30-40m and extends poleward in both hemispheres, as the NECC slope disappears. Anomalously high thermocline persists from 10°S-10°N, until at least January 1988. In June 1988, on the 20°S-10°N average the thermocline has returned to normal, after the upwelling episode of April 1988.

This evolution of the thermal structure is illustrated in Figure 4, which presents isotherm depths anomalies for all isotherms on the 0-400m depth range, at the beginning and during the peak phase of the ENSO event: in June 1986, the thermocline isotherms are deepened from 15°S-5°N, while they tend to shoal northward of 5°N. A year later, these isotherms are all displaced upward by more than 20m from 10°S to at least 10°N.

c. Heat Content.

Variations of heat content (not shown) are in agreement with thermocline displacements: heat accumulates at the beginning of 1986, and then is released, from June 1986 on, first around the equator, and extending poleward to 10°S-10°N. During 1987, average temperature from 10°S-10°N is more than 1°C below normal. Again this situation inverses rapidly in the first half of 1988, while going through the upwelling event.

These three parameters lead to the conclusion that the 1986-87 ENSO is characterized by a slow cooling of the warm pool, beginning at the equator in June 1986, extending to 10°S-10°N in mid-1987. Thermocline stays 30-40m shallower than normal, and average 0-300m temperature 1°C below normal, until sometime between January and April 1988: during that period a strong upwelling further cools the equatorial region, while heating poleward of 5° of latitude takes the thermal structure back to normal.

5. Comparison with GEOSAT Sea Level Anomalies.

It has been shown that results from cruise stations reflect long term variations associated with the ENSO event, but partly hidden by short scale variability. For part of the period of interest GEOSAT Sea-Level Anomaly data (GSLA) is available to complement cruise results. Several studies (Wyrtki, 1987, Miller *et al*, 1988, Tai *et al*, 1989) have shown that GSLA are good approximations of island sea level and dynamic height anomalies on scales larger than 1 month and a few hundredths of kilometers. Our purpose is to assess how much of the thermal variability captured by discrete cruises is also reflected in GSLA.

During the November 1986-November 1987 ERM period, six cruises are carried out, of which results can be used for comparisons. GSLAs are expected to better reflect vertically integrated parameters, like dynamic height (DH) and heat content (HCo, defined as above). To allow comparison , anomalies of DH and HCo are computed relative to the ERM period (11/86 - 11/87). At each latitude, we use an average of data from the 6 cruises, gridded on a 15 days, half-degree of latitude grid. To obtain a spatial smoothing comparable to what was used for GSLA, cruise data are smoothed alongtrack by a Hanning filter of 300km length.

Figure 5 shows scatter plots for DH and HCo vs GSLA. Correlation coefficients are 0.71 (DH) and 0.65 (HCo), but points are not independent and multiple smoothings do not allow for precise significance of these correlations. Rms difference about the fitted line for DH is about 4cm. Correlations are slightly better when limited to 10°S-10°N, which is in agreement with the fact that SL, DH and HCo are better correlated in this band because of the presence of a steeper pycnocline (Rébert *et al*, 1985).

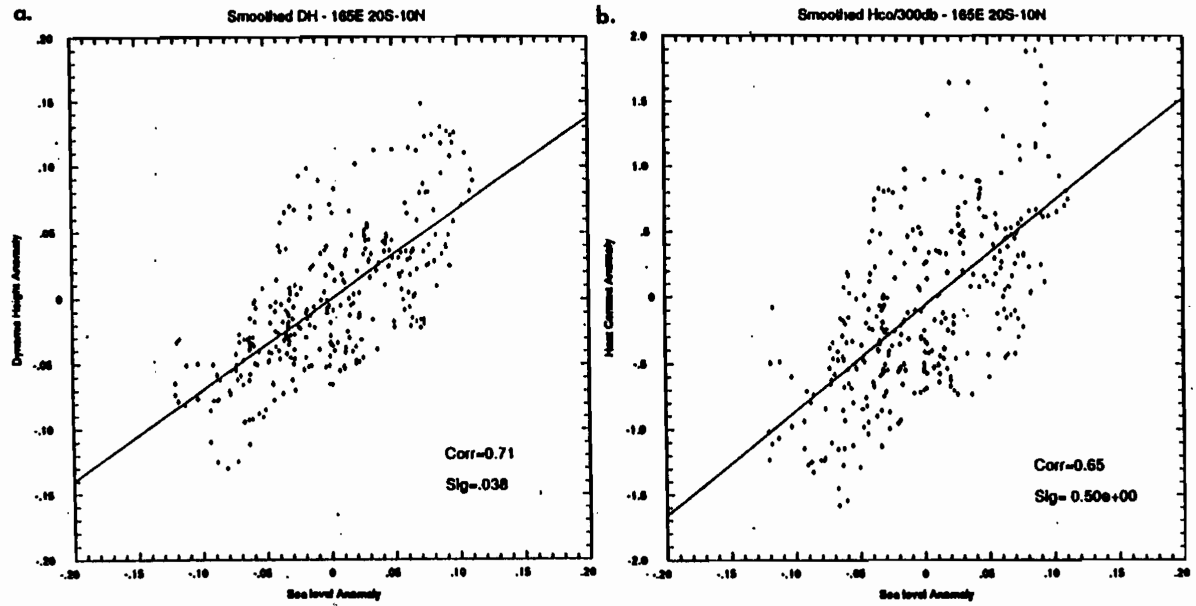


FIG. 5. Scatter plots of a) dynamic height anomalies and b) heat content anomalies versus GEOSAT sea level anomalies. Dynamic height and heat content values are obtained by interpolation to every 1/2 degree of latitude of 6 cruises stations to match GEOSAT 1/2 degree sampling. Solid line shows least squares linear regression fit.

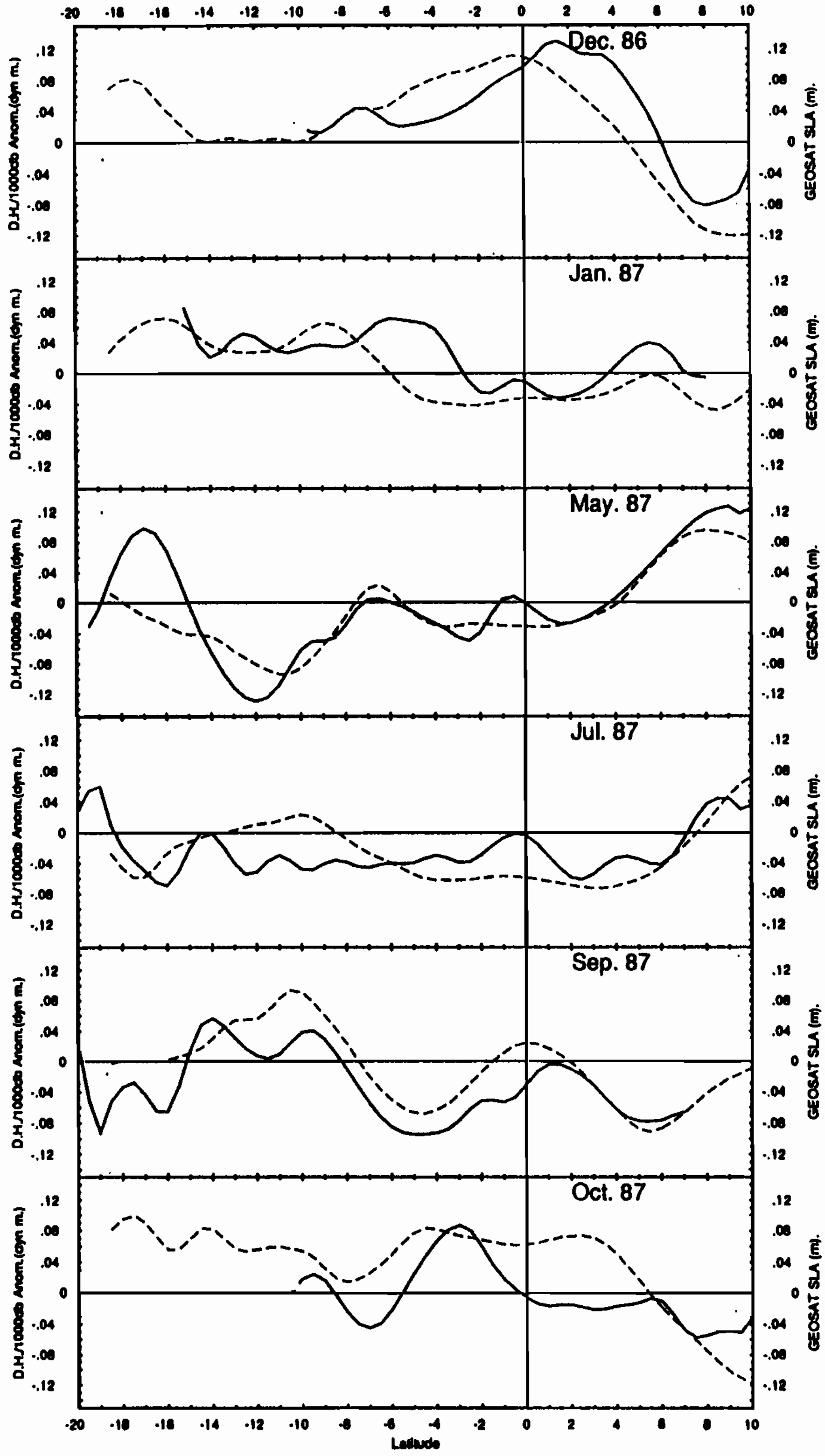


FIG. 6. Dynamic height (DHA) and GEOSAT sea level anomalies (GSLA) for each of the 6 cruises as a function of latitude. DHA: solid lines . GSLA: dashed lines.

More insight on relations between DH and GSLA can be obtained by comparing these two data sets for each cruise (Figure 6). The December 1986 cruise crosses a patch of high GSLA centered on the equator, which has been shown (Miller *et al*, 1988, Delcroix *et al*, this volume) to be associated to a downwelling Kelvin wave excited west of our zone. This high sea level is also reflected in DH, but displaced to the North by 2 degrees of latitude. In January 1987 this pulse has already disappeared, in GSLA and DH. The relatively high DH around 5°S is not reflected in GSLA; it must be noted that, from 5°S-5°N GSLA are close to the noise level (below 4cm). Best agreement is found in May 1987 for the Saga 02 cruise, excepted south of 14°S. There , cruise path is in the wake of Vanuatu islands, and sampling coarse. This is also a place of poor satellite coverage. North of 12°S good agreement may be explained in part by a lack of short scale variability for this particular cruise. In July 1987 DH is flat, excepted north of 5°N: agreement is good only along this northward slope. For the last 2 cruises DH are generally below GSLA, but difference does not exceed the 4cm rms difference.

Comparisons between HCo anomalies and GSLA (not shown) reveal the same indications as dynamic height, which shows that variability of sea level is mostly related to vertically integrated temperature variations.

It is noteworthy that, because of the generally low sea level state over which GSLA are computed, positive deviations are enhanced compared to what is referenced to a climatology: the most striking example is the positive pulse of GSLA at the beginning of 1987, which hardly appears in climatological anomalies, although it is a signature of important dynamics.

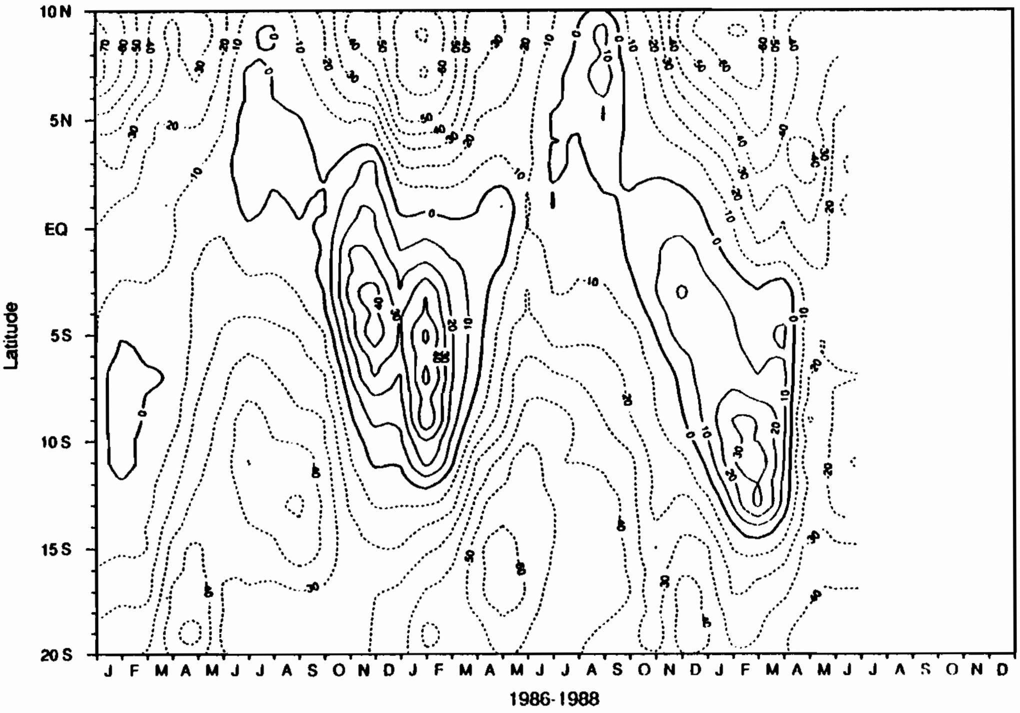
6. Indications from local wind forcing.

Anomalies of wind stress and wind stress curl along 165°E can provide some hints on the importance of local forcing in the observed variability of the temperature structure: from pseudo wind stress values from the FSU analysis, anomalies are computed relative to the 1979-81 + 1984-85 reference period, to allow comparison with thermal anomalies (Fig. 7).

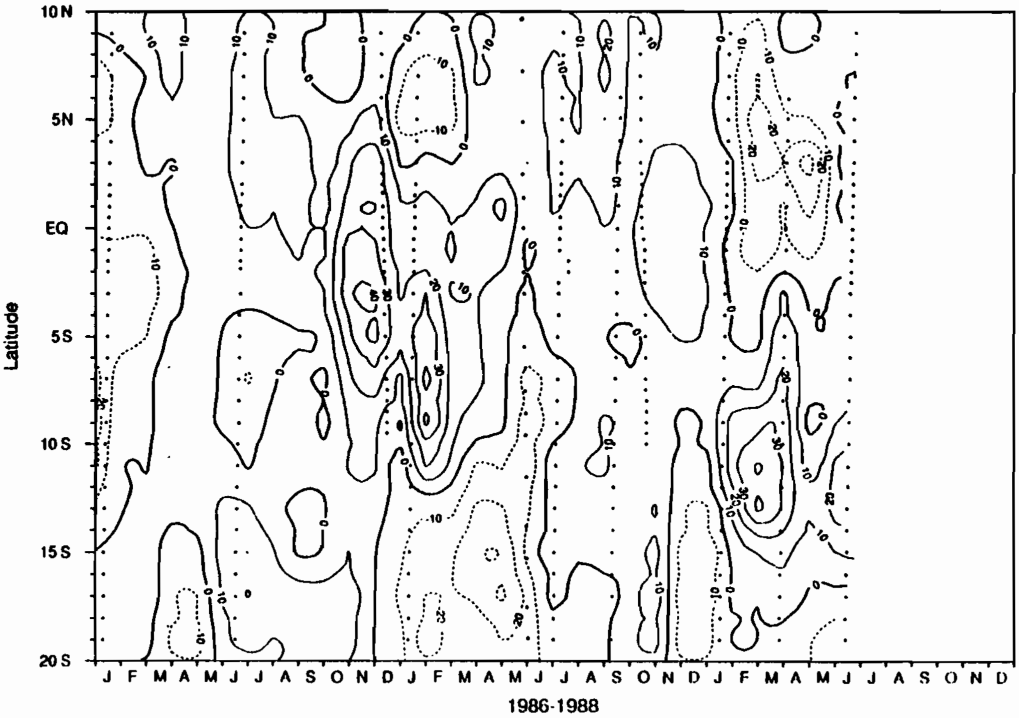
The first half of 1986 is characterized by a weak north-west monsoon south of the equator, and stronger trades, i.e. easterly anomalies. Beginning in October 1986 strong westerly anomalies appear corresponding to a strong monsoon, and also strong trades in the extreme north and south of the zone. Through 1987 generally westerly anomalies continue, peaking with the return of the seasonal monsoon, still abnormally strong. February-June 1988 is characterized by a return of the trades, strong in the north, and weak in the southern hemisphere.

Close to the equator the consequences of local forcing are generally indiscernible. However, in April-June 1988, the return of trades across the equator can explain the unusually strong upwelling reaching deep in the thermocline.

Away from the equator, poleward of 4-5 degrees, Ekman pumping can play a role (Fig. 8): caused mainly by the strong meridional gradients of the zonal wind stress component, Ekman pumping shows a tendency to lift up the thermocline from the end of 1986 to the end of 1987. This may qualitatively explain the poleward extension of anomalously high thermocline which develops after January 1987, and particularly in May 1987 south of 10°S, after the strongest anomalies. In the first half of 1988, effects of Ekman pumping reverse, consistently with the deepening of the thermocline observed poleward of 4 degrees in April and June 1988.



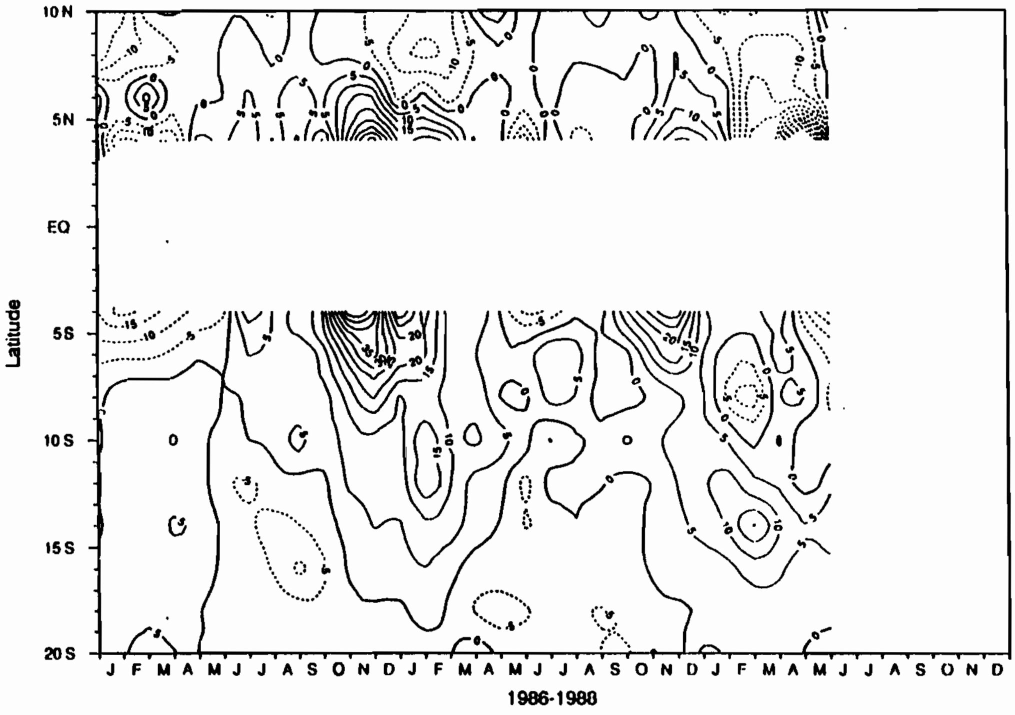
a. Tau-x 165E (m2/s2).



b. Tau-x Anomaly 165E (m2/s2).

FIG . 7. Zonal component of pseudo wind stress (a) and its monthly anomaly (b) for 1986-88, from Florida State University Analysis. Positive values eastward, solid contours. Negative values westward, dashed contours. Contouring interval is 10 m^2s^{-2}.

a. Ekman pumping , 165E (m/month).



b. Ekman pumping Anomaly, 165E (m/month).

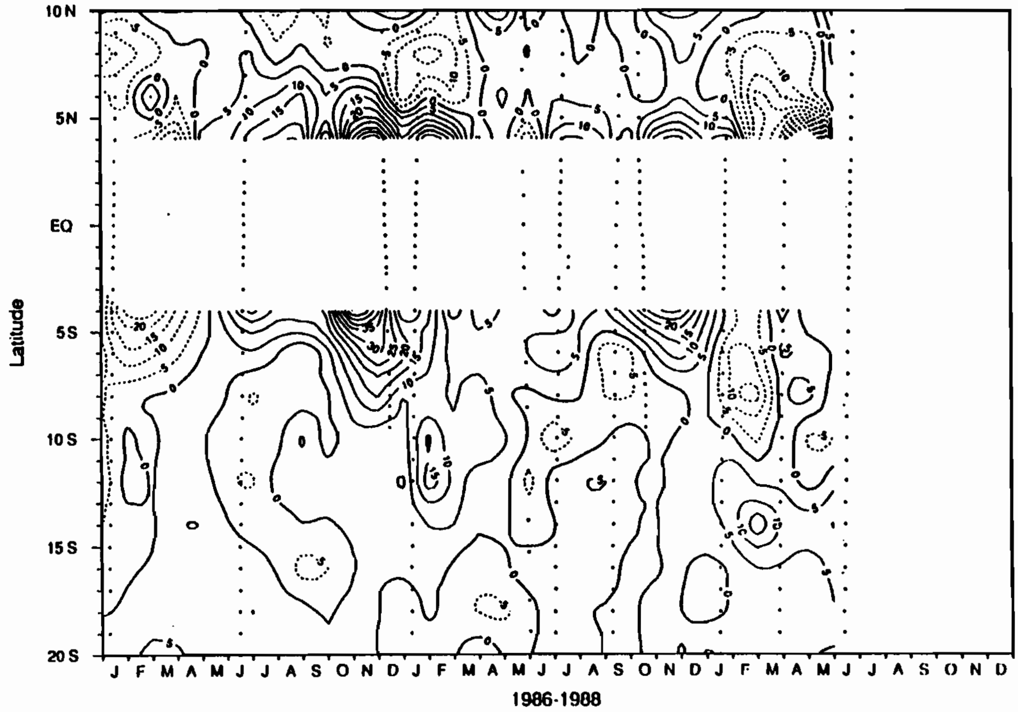


FIG. 8. Ekman pumping (a) and monthly anomaly (b), poleward of 4° of latitude, for 1986-88. Upward pumping positive, solid contours. Downward pumping, dashed contours. Contouring interval is 5 m.month^{-1}.

7. Conclusion.

Temperature data from 11 cruises carried out in the Western Pacific in 1986-88 have been used to study the variability of the vertical thermal structure during the 1986-87 ENSO event.

The 1986-87 ENSO along 165°E is characterized by a small increase of SST (0.5°C) in the 10°S-10°N band at the beginning of 1986, associated to a deepening of the thermocline of 20-30m. Then, SST decreases by about 1°C, and thermocline shoals by about 40m, beginning at the equator in January 1987, and extending poleward to 10°N-10°S. Average temperature above 300m is lowered of about 1°C.

GEOSAT Sea Level Anomalies are fairly correlated to cruise results for dynamic height and heat content, showing the same large scale patterns.

This anomalous thermal structure is maintained in part by equatorial wave dynamics, but also by Ekman pumping caused by anomalously westerly winds. This situation is rapidly reversed sometime between January and April 1988, where thermocline is deepened poleward of 5 degrees of latitude, and strong trades cause a return of equatorial upwelling.

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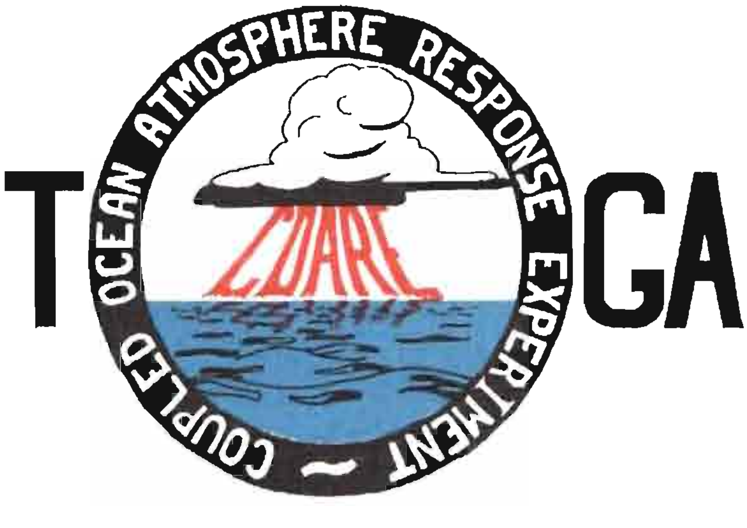

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