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Heat content displacement in the Pacific during the 1982-1983 El Niño event

Pacific Ocean
Heat content
El Niño 1982-1983
Linear model
Wind anomaly

Océan Pacifique
Contenu thermique
El Niño 1982-1983
Modèle linéaire
Anomalie de vent

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ABSTRACT

Heat content at 0-300 m depth is analysed in the tropical areas of the Pacific Ocean, using XBT data gathered along shipping lanes crossing the equator at 160°E, 160°W and 100°W, between 1979 and 1985. During the 1982-1983 ENSO event, areas north and south of the equator do not exhibit the same evolution at 160°E and 160°W. On the other hand, at 100°W, the heat content variation is similar on each side of the equator. A scenario of the heat content variations may be proposed as a result of planetary wave influences, as suggested by significant cross-correlations. A linear model, forced by FSU wind anomalies, agrees with the evolution of the heat content in the southern hemisphere and in the equatorial area but not in the northern hemisphere.

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RÉSUMÉ

Le déplacement du contenu thermique dans le Pacifique pendant l'El Niño 1982-1983

Le contenu thermique intégré de la surface à 300 m de profondeur est calculé dans la partie tropicale de l'Océan Pacifique, en utilisant les données XBT recueillies de 1979 à 1985 le long des lignes de navigation qui coupent l'équateur à 160°E, 160°W et 100°W. L'analyse du contenu thermique montre que pendant El Niño 1982-1983, les parties nord et sud de l'océan tropical ne présentent pas la même évolution à 160°E et 160°W. Par contre, à 100°W, les variations de contenu thermique sont semblables de part et d'autre de l'équateur. Les variations de contenu thermique peuvent être interprétées comme résultant de l'influence d'ondes planétaires, ainsi que le suggèrent des corrélations croisées significatives. Une simulation à l'aide d'un modèle linéaire simple, forcé par des anomalies de vent provenant du Florida State University (FSU), est en accord avec l'évolution du contenu thermique dans l'hémisphère Sud et dans la zone équatoriale mais pas dans l'hémisphère Nord.

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INTRODUCTION

The displacement of near-surface water masses in the tropical Pacific ocean during El Niño has recently been studied using oceanographic observations made during the 1982-1983 ENSO. For example Wyrtki (1985), from sea-level data, claimed that warm water stored in the equatorial area prior to El Niño moved during the event to higher latitudes. Halpern (1984; 1987) has followed fluctuations of heat storage in the eastern Pacific from equatorial moorings and Dessier and Donguy (1987) have described the same features using XBT data. XBT data collected from merchant ships have proved to be very useful and have recently been used extensively. For example, Meyers and Donguy (1984) have pointed to the influence of advection by the North Equatorial Countercurrent (NECC) in explaining the transport of warm water from west to east. Kessler and Taft (1987) have studied the anomalies of zonal geostrophic transports during the 1979-1984 period. White *et al.* (1985) have presented a scenario prior to the event and have found a coherent evolution of the

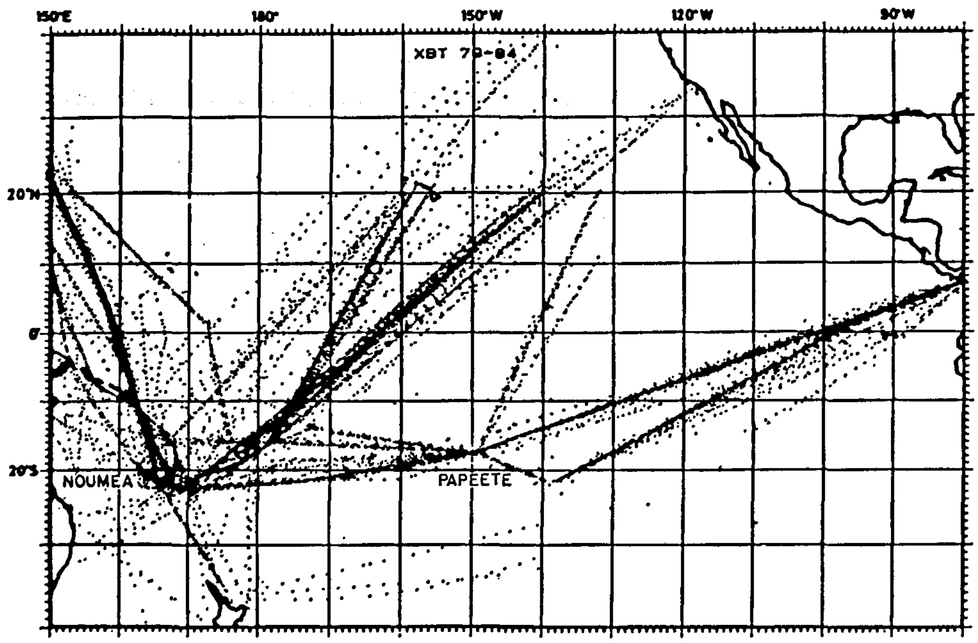

Figure 1
Ships of opportunity network in the Pacific. Dots represent XBT profiles from 1979 to 1984.

temperature field prior to the intensification of the 1982-1983 ENSO event for approximately one full year. A number of modelling experiments have been carried out using different wind products, for determining either the seasonal cycle or the interannual variability of the heat content (or the sea level) or for simulating particular El Niño events of the tropical Pacific.

McPhaden *et al.* (1988) have examined simulations of the seasonal cycle of the sea-surface dynamic topography, using a multimode linear model forced by three different wind products over the 1979-1981 period, and have compared them to XBT and tide gauge observations averaged over the same period. Inoue *et al.* (1987), using a single mode linear model, have investigated the interannual variability for the period 1974-1982 and compared model results with XBT data. Pares-Sierra *et al.* (1985), with the same model, estimated seasonal and interannual horizontal heat transport in the tropical Pacific between 1969 and 1979 and suggested that the adiabatic process is dominant in the total heat balance. Zebiak (1988) has studied the tropical heat content variability in a very similar model but forced with 1970-1987 winds, focusing the discussion on control of ENSO cycles by storage of heat near the equator, at least in coupled ocean-atmosphere models. Busalacchi and Cane (1985) have compared a linear wind-driven solution (with four vertical modes) to the observed sea level during the 1982-1983 El Niño, while Philander and Hurlin (1988) have solved the heat budget problems of the tropical Pacific Ocean in 1982-1983 by analysing data from a realistic simulation with an Ocean General Circulation Model.

We here report an effort to describe the heat content evolution along the equator and to explain such features as the asymmetries between the northern and southern hemispheres. The next section provides a description of the data used in the study. Heat content in each hemisphere, along XBT tracks, is investigated in the third section. The fourth section, using cross-correlations, presents a scenario of heat transfer for the 1982-1983 El Niño, involving eastward displacement of heat content along the equator. The fifth section constitutes an attempt to simulate heat content anomalies from a linear model.

DATA

Temperature structure has been monitored by expendable bathythermographs (XBT) launched from volunteer observing (merchant) ships in a programme jointly operated by France and the USA, since 1979. The programme involves sounding to 450 m depth at intervals of approximately 60 nautical miles along three main shipping routes (Fig. 1): New-Caledonia - Japan, crossing the equator at 160°E; Fiji-California, crossing the equator at 160°W; Tahiti-Panama, crossing the equator at 100°W. The time between cruises is typically 2-4 weeks.

Heat content H, from surface to depth D, is given by the relation (Rebert *et al.*, 1985):

$$H \sim \int_D^0 T(z)\,dz$$

with $T(z)$ the temperature at depth z. As some XBT profiles do not penetrate below 300 m, D has been fixed at 300 m. Consequently, the heat content is proportional to the mean temperature of the upper 300 m of the ocean.

Monthly heat content is shown (Fig. 2-4) in space-time diagrams along the three shipping routes. The units are months (on the abscissa) and degrees of latitude (on the ordinate). Due to uneven sampling, some grid-boxes have no observations. In order to obtain smoothed values to be used for automatic contouring, at each grid point, a method of linear interpolation is used. This method, called kriging, is based on the

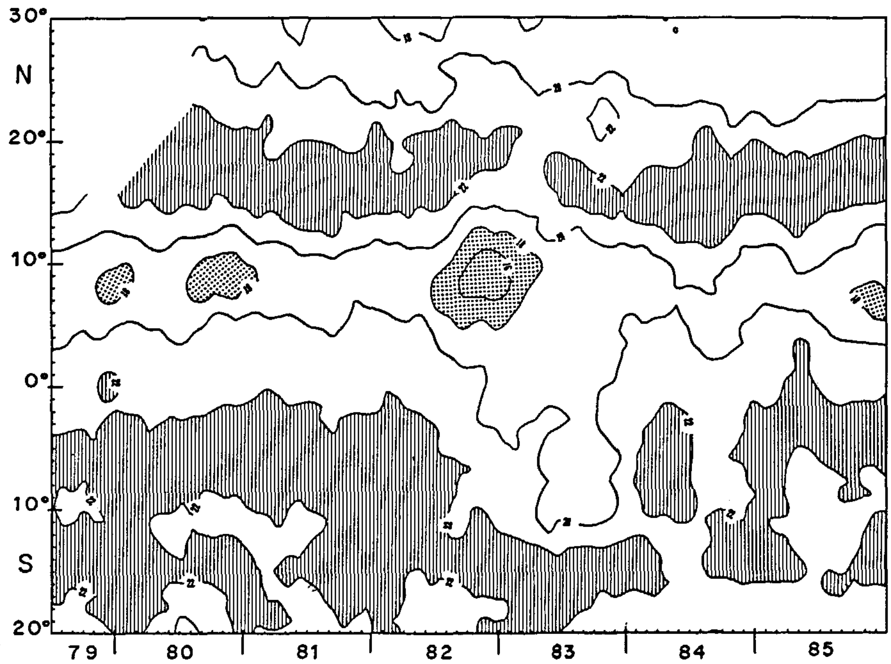

Figure 2
Mean temperature (0-300 m) latitude-time series, 1979-1985, along the New-Caledonia - Japan route crossing the equator at 160°E (western Pacific). Maximum is highlighted with hatching. Minimum is highlighted with dotting.

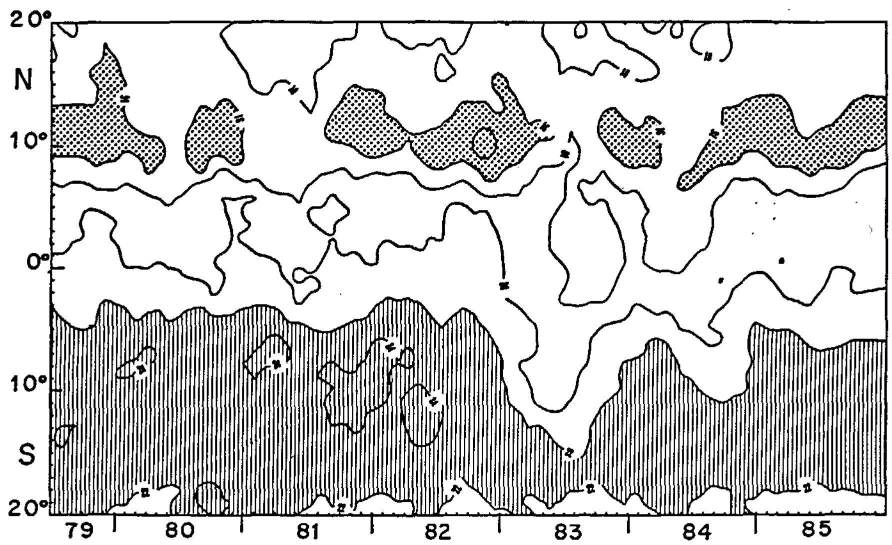

Figure 3
Mean temperature (0-300 m) latitude-time series, 1979-1985, along the Fiji-California route crossing the equator at 160°W (central Pacific). Maximum is highlighted with hatching. Minimum is highlighted with dotting

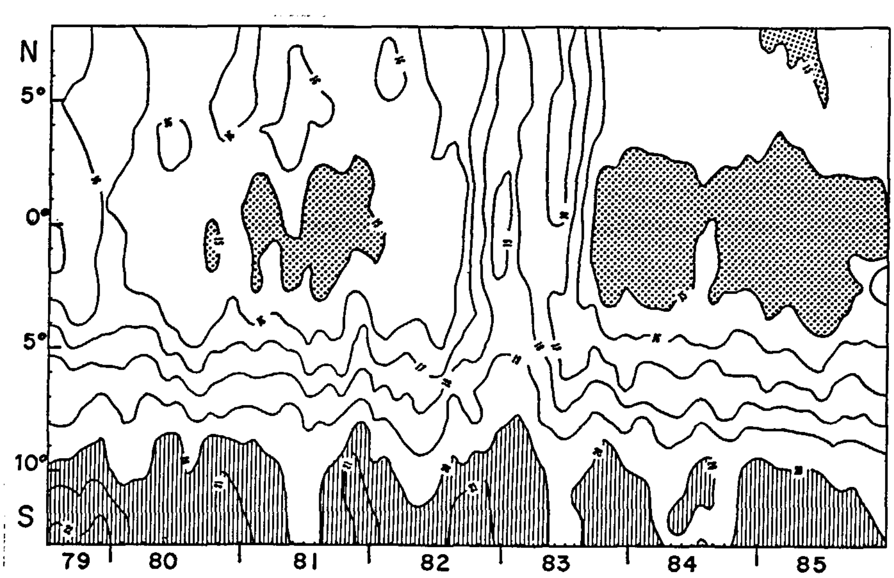

Figure 4
Mean temperature (0-300 m) latitude-time series, 1979-1985, along the Tahiti-Panama route crossing the equator at 100°W (eastern Pacific). Maximum is highlighted with hatching. Minimum is highlighted with dotting.

theory of regionalized variables (Matheron, 1965; 1970) which characterizes a phenomenon spreading in space or time and revealing there a spatial pattern. The observation field is supposed isotropic in space and time.

In the western (160°E) and central Pacific (160°W; Fig. 2 and Fig. 3), two maxima of heat content are centered at 10°S and 20°N respectively and separated by a minimum at approximately 10°N in the NECC trough. In the eastern Pacific (100°W; Fig. 4), a strong maximum exists south of 10°S, and a strong minimum corresponding to the equatorial upwelling at the equator; an important gradient at about 5°S separates the equatorial minimum from the southern maximum; this gradient is connected to the SST front usually located in the vicinity of the Galapagos Islands (Dessier and Donguy, 1985). The heat content exhibits significant interannual variability except south of 20°S and north of 10°N (Fig. 2, 3 and 4). The variations in the west and in the centre are very similar and are characterized in 1982-1983 by decreased heat content in the equatorial area as far south as 10°S. In the east, the 1982-1983 variation is characterized by a strong increase of heat content in the equatorial area as far north as 8°N.

HEAT CONTENT IN EACH HEMISPHERE

In order to obtain large-scale variations of heat content in each hemisphere, vertically-averaged temperatures (Fig. 2-4) are integrated horizontally from 20°S to the equator and from the equator to 10°N (respectively 10°S to the equator and from the equator to 8°N for the eastern transect). Monthly anomalies are computed relative to the July 1979-June 1982 monthly mean (July 1979 marking the beginning of the observations). The monthly mean reference is considered as the mean reference before El Niño. It avoids the strong anomaly due to the 1982-1983 El Niño and, at the same time, maintains the interannual trends. The variation with time of the mean temperature anomaly is then considered in connection with the wind field from FSU as presented in the El Niño atlas (Leetmaa and Witte, 1984).

At 160°E (Fig. 5), from the equator to 10°N, a weak anomaly (+0.5°C) is present from mid-1981 to mid-1982 prior to the El Niño event. The anomaly drops suddenly in May 1982 to reach a deep minimum of −2.6°C in January 1983. This drop is related to a strong equatorial westerly wind-burst occurring in March 1982 from 140 to 160°E. The maximum of negative anomaly is reached in January 1983. Then, at the equator, easterly winds appear which induce a decrease of the negative anomaly until June 1983. Although at this time the wind has returned to the usual situation (trade wind), the heat content still presents a negative anomaly.

From the equator to 20°S, at 160°E, the heat content anomaly before El Niño is weakly positive (+0.3°C). This anomaly drops suddenly in July 1982 and decreases until October 1983 when the anomaly reaches −1.8°C. This drop is due to the anomalous southwest wind prevailing in the area, starting in June 1982 (Meyers *et al.*, 1986). Then, the anomaly starts to diminish rapidly, approaching usual conditions at the beginning of 1984.

Meyers and Donguy (1984) have already pointed to the coincidence between reduced heat storage in the northern hemisphere (1°S-5°N) and a maximum flow of the NECC between June 1982 and March 1983. In the equatorial area, the scarcity of XBT measurements is an impediment to geostrophic calculations, and the estimation of the zonal currents from thermal profiles is uncertain at 160°E. However, a special equatorial isotherm distribution was observed from September to December 1982 when westerly winds prevailed: there was contraction of the depth interval between the 15 and 20°C isotherms and a spreading of the 20-25°C isotherms. This latter thermal pattern suggests the existence of a surface eastward flow along the equator (Donguy *et al.*, 1984 *a*). Consequently, the occurrence of the heat content anomalies beginning in July 1982 in the southern hemisphere seems to be connected with this equatorial eastward flow. This equatorial jet may occasionally extend into the southern hemisphere as far south as 10°S, as shown by the dynamic topography estimated from XBT observations and the sea level slope (Donguy *et al.*, 1986).

In summary, at 160°E, the pattern of the anomaly in each hemisphere is different. In the northern part, the anomaly starts in May 1982 and reaches its negative extreme in January 1983; in the southern part, the anomaly starts in July 1982, reaches its negative extreme in October 1983 and decreases slowly thereafter.

At 160°W (Fig. 6), from the equator to 10°N, the anomaly before El Niño is mainly positive (+0.5°C). The anomaly starts to decline in October 1982, reaching −1.0°C in February 1983 and then increasing until May 1983. This anomalous behaviour may be related to the evolution of the wind field in the area: the anomaly increased between October 1982 and

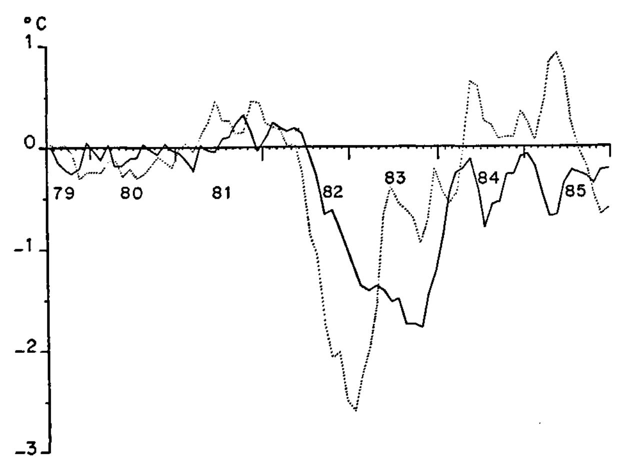

Figure 5

Western Pacific: mean temperature anomaly (0-300 m), 1979-1985, in degrees Celsius, integrated horizontally from the equator to 20°S (full line) and from the equator to 10°N (dotted line).

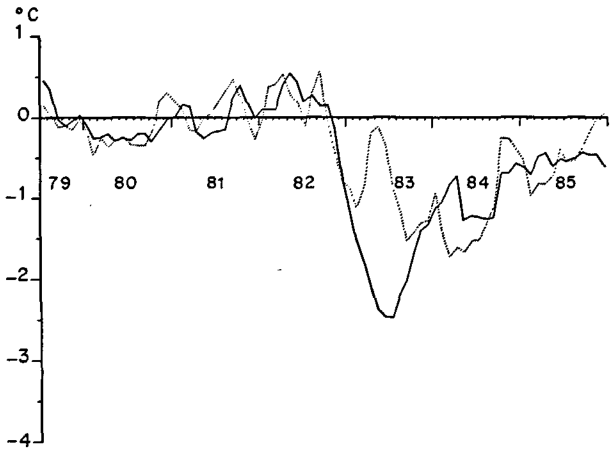

Figure 6
Central Pacific: mean temperature anomaly (0-300 m), 1979-1985, in degrees Celsius, integrated horizontally from the equator to 20°S (full line) and from the equator to 10°N (dotted line).

February 1983 when the wind anomaly increased; it diminished between February to May 1983 when the wind anomaly decreased (Leetmaa and Witte, 1984). Two other negative extreme anomalies occur in 1983 and in 1984.

From the equator to 20°S, at 160°W, the anomaly is positive prior to El Niño (+0.5°C), drops suddenly in November 1982 to a minimum of −2.5°C in June 1983 and then slowly increases until 1985. The sudden drop in November 1982 is due to the reversal of the easterly wind to westerly; the anomaly change in June 1983 may be connected to the fresh onset of easterly winds in this area.

Kessler and Taft (1987) have shown a maximum flow of the NECC at 160°W in December 1982-January 1983, corresponding to the first major anomaly in the northern hemisphere. In the southern hemisphere, the sudden drop in November 1982 is related to the eastward flow observed simultaneously at 159°W (Firing *et al.*, 1983); this equatorial countercurrent probably extends further southward as suggested by the flat topography of the isotherms (Donguy *et al.*, 1984*b*).

In summary, as at 160°E, the patterns of the anomaly in each hemisphere are different. They begin at almost the same time (October-November 1982), but in the north three individual peaks (in February, October 1983 and April 1984) are observed, whereas in the south only one strong peak is observed.

At 100°W (Fig. 7), from the equator to 8°N, the anomaly is weakly negative before El Niño, as already pointed out by Donguy and Dessier (1983) for sea-surface temperature. The anomaly becomes positive in May 1982 and increases suddenly in August 1982, reaching a maximum of +2.8°C in December. Positive values persist until September 1983 and then become negative (−1.0°C) in October 1983. This feature is consistent with the occurrence of eastward currents reaching as deep as 200 m in the vicinity of the equator in December 1982 and April 1983 (Halpern, 1987).

From the equator to 10°S, the anomaly is weakly negative before El Niño and becomes positive at the same time as in the northern hemisphere. It increases to +2.0°C and then becomes negative at the same time as in the northern hemisphere.

In summary, in the eastern Pacific, the patterns of the anomaly in each hemisphere are similar: they become positive and then negative at the same time. The sudden disappearance of the positive anomaly in both hemispheres and its replacement by a small negative anomaly in October 1983 is probably due to the termination of the wind anomaly in the central Pacific and the reestablishment of normal wind conditions.

Considering heat content anomaly patterns (Fig. 5, 6, 7), it appears that the El Niño signal is different in the northern and southern hemispheres for the western and central Pacific: only one event occurs in the southern hemisphere but several peaks at different times and with different amplitudes appear in the northern hemisphere.

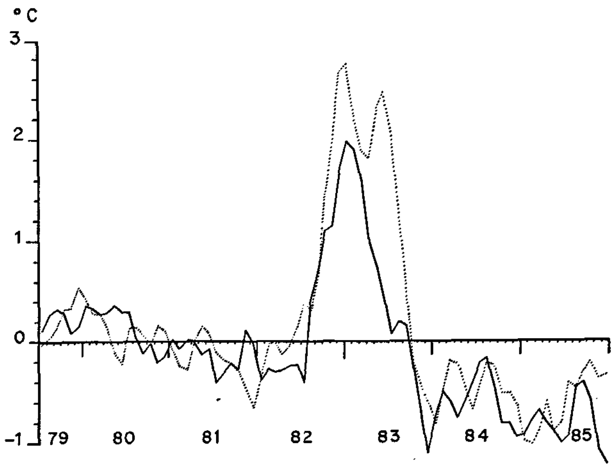

Figure 7
Eastern Pacific: mean temperature anomaly (0-300 m), 1979-1985, in degrees Celsius, integrated horizontally from the equator to 10°S (full line) and from the equator to 8°N (dotted line).

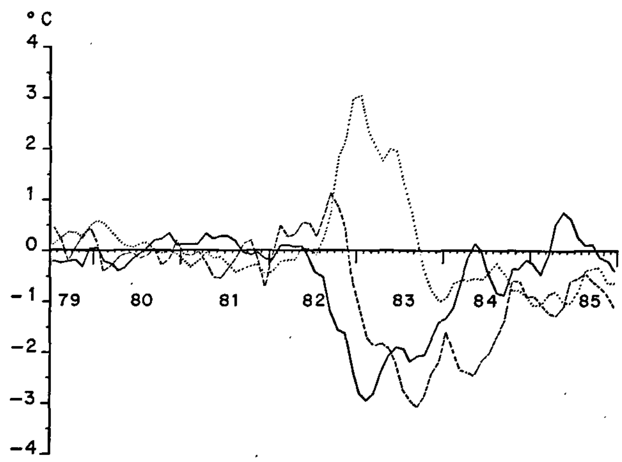

Figure 8
Mean temperature anomaly (0-300 m), 1979-1985, in degree Celsius, integrated horizontally from 5°S to 5°N, in the western Pacific (full line), in the central Pacific (dashed line) and the eastern Pacific (dotted line).

TIMING OF THE HEAT TRANSFER

The scenario of the 1982-1983 El Niño from January 1982 to May 1983 is again considered at 160°E, 160°W, and 100°W using the heat content anomalies integrated along the equatorial band (5°N-5°S; Fig. 8).

Along the equatorial band, from 1979 to June 1982, the heat content anomaly in the equatorial Pacific is close to zero. However, the heat content anomaly integrated over a latitude band (20°S-0 and 0-10°N) in the western (Fig. 5) and central (Fig. 6) Pacific seems to indicate a slight increase of the heat content during this time.

Wind stress anomalies presented for 160°E, 160°W and 100°W (Fig. 9) show that the occurrence of anomalous winds is particularly evident in the central Pacific (160°W), starting in September 1982. However a weak anomaly is noticeable at 160°E starting in June 1982 and at 100°W starting in January 1983. Before June 1982, with normal wind conditions prevailing in the equatorial Pacific, isotherms were deep in the western Pacific and heat content storage was important by piling up of the water (Wyrtki, 1985). According to Gill and Rasmusson (1983), westerlies bloew for 6 months in the western Pacific starting in June 1982 and the westerly wind anomaly extended eastward along the equatorial area at approximately 0.5 m/s.

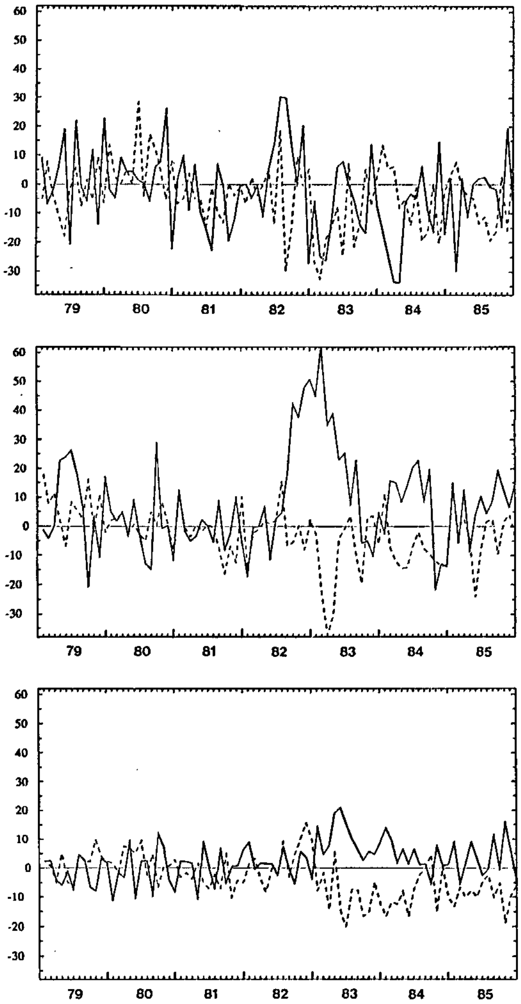

Figure 9

Wind stress anomalies at the equator: A) at 160°E, B) at 160°W and C) at 100°W (zonal component, full line; meridional component, dotted line).

At 160°E, west of the westerly wind anomaly located in the central Pacific, the isotherms become shallow and heat content decreases (Fig. 8) due to Rossby waves generated by westerly anomalies that propagate freely into the western Pacific.

The patch of the westerly wind anomaly in the central Pacific extends eastward from 180° (Leetmaa and Witte, 1984). In an area located east of the patch, heat content first increases (Fig. 8 for 160°W and 100°W) due to the passage of a Kelvin wave generated at the eastern edge of the patch. It then decreases following the passage of an upwelling Kelvin wave generated at the western edge of the patch (Tang and Weisberg, 1984). Irregularities observed during the decrease of heat content are due to the arrival of cooling Kelvin waves from reflection on the western boundary, whose effect is to terminate the event, returning the heat content into smaller values and the ocean into a cold situation. This process has been studied in a coupled tropical atmosphere-ocean model by Battisti (1988), who emphasizes the role of the western boundary reflections for the termination of a warm event [in the simple case of Tang and Weisberg (1984), the western edge of the patch plays this role].

Cross-correlations are consistent with this scenario (Fig. 10). A significant negative correlation (A; −0.7), appears between the average temperature anomaly in the west (160°E) and that in the east (100°W) with only one month lag (East leading West). This correlation, involving the main negative peak of heat content in the West (160°E) and the main positive peak in the East (100°W) occurring at the beginning of 1983 (Fig. 8), is due to the nearly simultaneous arrival of Kelvin waves at 100°W and of Rossby waves at 160°E, both generated by the wind anomaly located in the central Pacific (Fig. 9).

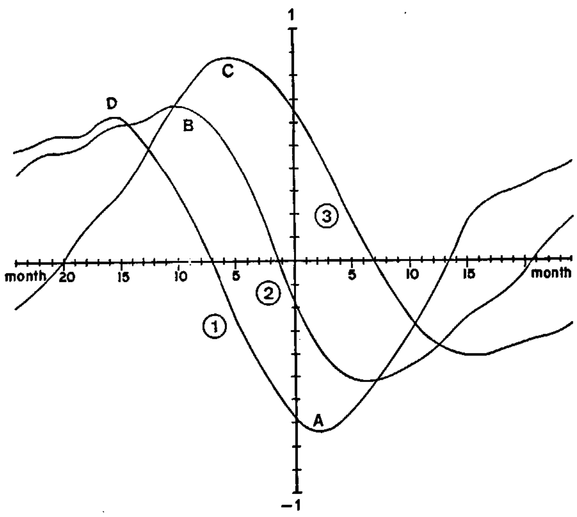

Figure 10

Cross-correlations between mean temperature anomalies (0-300 m), 1979-1985, (5°S-5°N) in the western Pacific and in the eastern Pacific (1); in the central Pacific and in the eastern Pacific (2); in the western Pacific and in the central Pacific (3). Significant correlations are denoted A, B, C, and D.

A significant positive correlation (D; +0.6), appears between the average temperature anomalies in the West (160°E) and East (100°W), with a 15-month lag (West leading East). This correlation involves mainly the negative peaks corresponding to the heat content minimum in the West (beginning 1983) and in the East (beginning 1984; Fig. 8). These peaks correspond to the intensity maximum of the wind anomaly (Fig. 9). However, as the peaks are not well defined, the lag length is not accurate.

A significant positive correlation (B; +0.7), also appears between the average temperature anomaly in the centre (160°W) and that in the East (100°W) with a 9 month lag (centre leading East). This correlation involves the positive peak of heat content which appeared first in the Centre (September 1982) and then in the East in 1983 in the form of a double peak, as reported by Donguy *et al.* (1984*c*). Heat content was maximum at both locations east of the westerly wind anomaly (Fig. 8).

A significant positive correlation (C; +0.9), appears between the average temperature in the West (160°E) and that in the Centre (160°W) with a 5-month lag (West leading Centre). This correlation involves two well-defined negative peaks corresponding to the heat content minimum (beginning 1983 in the West and mid-1983 in the Centre) at the time of the wind anomaly maximum (Fig. 9).

COMPARISON WITH LINEAR WIND DRIVEN SIMULATION

Variations of pycnocline depth have been simulated using a linear wind-driven model similar to that of Cane and Patton (1984). Briefly, the shallow water equation is solved on an equatorial β-plane, assuming the long-wave, low-frequency approximation. The equations result considering a single baroclinic mode with equivalent depth 86 cm and internal wave speed 2.9 m/s, or a reduced gravity two-layer system with an active upper layer at 150 m with a $\Delta\rho/\rho = 5.7 \times 10^{-3}$ and a deep layer at rest (Cane, 1984; Zebiak, 1988). In this framework, pycnocline anomaly is proportional to heat content anomaly.

The model is forced by wind stress anomalies derived from FSU pseudo stress analyses. Monthly anomalies are formed by referencing each month to a monthly mean calculated for the period July 1979-June 1982, for the sake of consistency with XBT data analyses. Model results have been sampled at the same location and time as XBT data, in order to obtain a qualitative comparison (Fig. 11).

In the western Pacific (Fig. 11 A), the model calculation exhibits the same time variation as the data for the 1982-1983 event. A strong negative anomaly of thermocline depth develops, from mid-1982 until September 1984 in both hemispheres. However, the amplitude of the major peak is smaller in the northern than in the southern part, in disagreement with the data. At the three locations, the model simulation exhibits in 1984-1985 large depth fluctuations which are not correlated with heat content fluctuations. This may be due to averaging method of the wind anomalies and the long trend which is known to exist in the ship wind data (Posmentier *et al.*, 1985). However, heat content anomalies show stronger variability after the 1982-1983 event than before. This feature is also confirmed by data analysis carried out in the central and the western-south Pacific (Hénin, personal communication).

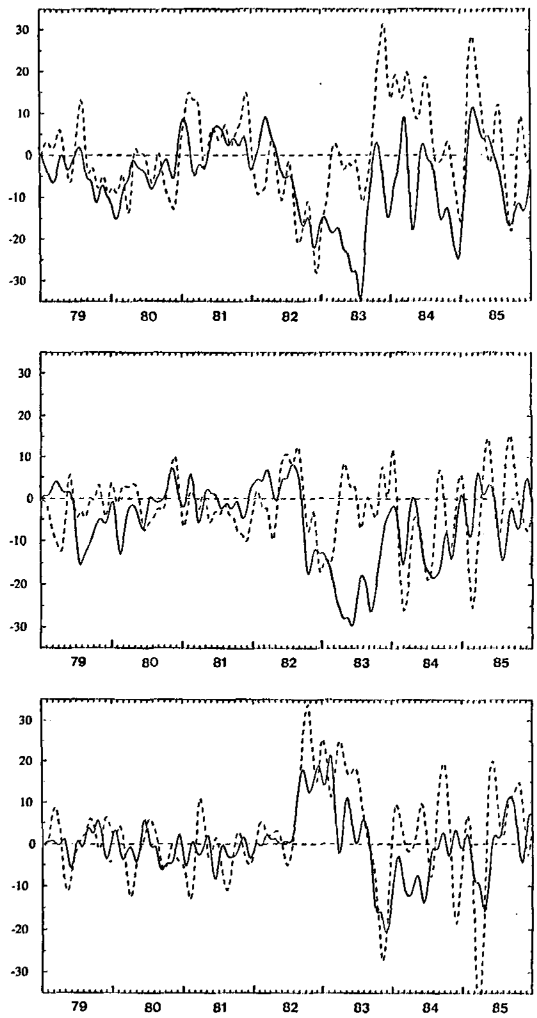

Figure 11
Model thermocline depth anomaly (in metres) in function of time: A) on the western Pacific track; B) on the central Pacific track; and C) on the eastern Pacific track (southern hemisphere, 0-16°S: full line; northern hemisphere, 0-10°N: dotted line).

In the central Pacific (Fig. 11 B), in the southern hemisphere, the situation leads to the same anomalies: the thermocline depth increases until mid-1982, then decreases and reaches a minimum in May 1983, as noted in the data. However, the recovery from the El Niño event is faster in the model than in the data. In the northern hemisphere, the simulation is very noisy and hardly resembles to the heat content evolution, although both bear the same trend after El Niño.

In the Eastern Pacific (Fig. 11 C), the model reaches a positive maximum simultaneously (October 1983) in the northern and southern hemispheres, this feature being followed by a negative anomaly beginning in September 1984 and reaching its minimum in December 1984, in agreement with the observations. However, the amplitude of this minimum is more pronounced in the model than in the XBT data. In the western and central sections alike, the model results show a strong variability after El Niño as outlined above. A significant negative trend from 1979 to the beginning of 1982 is present as in the data (Fig. 7). This trend does not appear in the data analysis at the equator (Fig. 8) but only in the integrated heat content anomaly in south and north of the equator (Fig. 7); there is also a similar trend in model results in the equatorial band.

In the northern hemisphere, the discrepancy may be connected with the inability of the model to reproduce correctly the NECC ridge. This problem has been already noted by Inoue *et al.* (1987) in comparing simulated and observed situations prior to El Niño, and by McPhaden *et al.* (1988) in their study of the seasonal cycle of surface dynamic height. Such model calculations are linear and the neglected terms (*i. e.* thermodynamic and non-linear terms) might be invoked to explain the discrepancy. However heat content (or surface dynamic topography) is thought to be well represented by linear theory, as noted in the fully non-linear calculations. Moreover, Harrison *et al.* (1988), with an ocean general circulation model, have noted a bad hindcast skill in the vicinity of the NECC ridge. Uncertainty in estimating the wind field in areas where wind stress curl varies rapidly might be the main reason for the discrepancy. On the other hand, the calculation is strictly adiabatic and results solely from dynamic adjustment. The fluctuations in heat content due to dynamic and thermodynamic processes seem to be roughly similar in a coupled model (Zebiak and Cane, 1987) and in an Ocean General Circulation Model (Philander and Hurlin, 1988).

At the equator, Tang and Weisberg (1984), using a linear calculation, pointed to the role of a moving wind anomaly patch in the duration of the eastern downwelling in comparison with the case of a stationary patch. Their results compare qualitatively with the temporal evolution at different longitudes of the XBT's and show the same opposition at 160°E and 100°W as the observations (Fig. 8).

It is unlikely that El Niño precursors exist in the surface mixed layer, as its thermal damping time is small (only a few months) relative to ENSO time scales, but in the subsurface thermal structure (White *et al.*, 1985). Consequently, the heat content of the Pacific within the equatorial band must be above the mean value (Cane, 1986) or equivalently, the zonal slope along the equator would be stronger than normal before the event. Simulation in the equatorial band is consistent with this assumption, but it is difficult to claim that such a condition is met in this analysis, because three XBT lines over the pacific Ocean are not sufficient to permit an estimate of the heat content which requires a zonal integration along the equator. However the observations present a slight trend (increased heat content in the western and central XBT track, decreased heat content in the eastern track) before El Niño within the whole tropical area (Fig. 5, 6, 7) but not in the equatorial zone itself (Fig. 8).

CONCLUSION

Heat content anomalies have been calculated using 1979-1985 XBT data on the tropical part of three regular Pacific merchant ship tracks, crossing the equator at 160°E, 160°W and 100°W. The evolution of the anomalies exhibits a clear disymmetry between the northern and southern hemispheres on the western and central tracks. During the 1982-1983 El Niño, on the western track, the northern hemisphere anomaly is stronger than the southern one; the converse is the case on the central track. To the east, southern and northern anomalies exhibit similar variations. The evolution in time of the anomalies may be explained referring to Tang's and Weisberg's (1984) notions and to the work of Battisti (1988) on the influence of planetary waves. A simple linear modelling simulation, using FSU wind anomalies, is in good agreement with XBT data mainly in the southern hemisphere. In the north, the evolution differs from the data, probably due to the inaccurate estimation of the wind stress field in areas where wind stress curl varies rapidly. This feature has been already noted by Inoue *et al.* (1987) and also in the non-linear model simulation reported by Harrison *et al.* (1988). Nevertheless, the simulation also confirms the disymmetry between the northern and southern hemispheres. The heat content anomaly integrated over the tropical area shows a slight increasing trend on the western and central tracks and a decreasing trend on the eastern track prior to June 1982. The simulation exhibits such a slight trend only in the equatorial band. As these trends are slight and could be only noise, caution should be exercised in interpreting them as precursors without which the sudden appearance of westerlies near the date line would not produce the event.

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