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Sea surface salinity changes along the Fiji-Japan shipping track during the 1996 La Niña and 1997 El Niño period

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Abstract. Sea-surface salinity (SSS) changes during the 1996 La Niña and 1997 El Niño events are analysed along the Fiji-Japan shipping track, based on 20 thermosalinograph sections. In the equatorial band, above-average SSS (35.2 to 35.4 instead of 35) were observed in 1996, consistent with a well-marked south equatorial current, an unusually-strong equatorial upwelling, and below-average precipitation (P). From January to August 1997, the SSS decreased sharply from 35.2 to 33.8 (lowest recorded monthly value over the last 20 years), compatible with a reversal of zonal current, the occurrence of equatorial downwelling, and above-average P. From September to November 1997, the SSS remained almost constant (34.2), consistent with the opposite effects of eastward current, likely bringing low saline water from the Pacific warm pool, and of evaporative cooling, vertical mixing and below-average P which all tend to increase SSS. The potential impacts of the observed SSS changes on sea level are discussed.

Introduction

The distribution of salt in the tropical oceans and its variability are potentially important in better understanding the ocean-atmosphere coupled system. In the tropical Pacific, the average distribution of Sea Surface Salinity (SSS) is characterised by a relatively low value in the Inter Tropical and South Pacific Convergence Zones (ITCZ, SPCZ), and in the so-called warm pool in the western equatorial region where Sea Surface Temperature (SST) is over 28°C [*Levitus et al.,* 1994]. In these three areas, the low value of SSS reflects primarily the negative evaporation minus precipitation (E-P) budget resulting from light winds and high rainfall rates.

Ignoring the high-frequency variability, the SSS changes happen essentially at the seasonal time scale in the ITCZ and SPCZ, and at the ENSO (El Niño Southern Oscillation) time scale in the warm pool region [*Delcroix et al.,* 1996]. This latter region has been called also the "fresh pool" (SSS≤35); its eastern edge is characterised by a marked salinity front centred around the 35 isohaline, and it separates the less saline water in the west from the more saline water in the central basin [*Picaut et al.,* 1996; *Delcroix and Picaut,* 1998; *Hénin et al.,* 1998]. Based on observational and modelling studies covering the pre-1996 period, these last authors demonstrated that the eastern edge of the warm and fresh pool was displaced eastward during El Niño and westward during La Niña periods, chiefly in response to zonal advection of heat and salt by anomalous currents. Such zonal displacements, in phase with the SOI (Southern Oscillation Index), are associated with changes in local mixed layer temperature and salinity, barrier layer thickness and the world's greatest tuna harvest [*Ando and McPhaden,* 1997; *Lehodey et al.,* 1997].

As a complement to some of the previously-cited studies, the goal of the present note is to analyse the SSS changes occurring along a shipping track running from Fiji to Japan (Figure 1). Interestingly, the 1996-97 period of study encompasses the 1996 La Niña-like event together with the first year of the strongest El Niño of the century. For comparison purpose and to help in the interpretation, the SSS analysis will be complemented by an analysis of Sea Level Anomaly (SLA), 0/700 dbar Dynamic Height Anomaly (DHA), and vertical thermal structure obtained along the same shipping track.

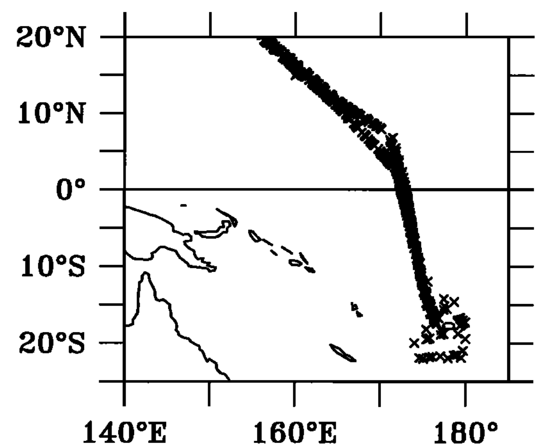

Figure 1. Location of the thermosalinograph, TOPEX/Poseidon and XBT derived measurements along the Fiji - Japan shipping track during 1996-97. The crosses denote the location of the XBT casts. The track separation within 2°N-12°N reflects that 7 out of the 20 shipping tracks call in Tarawa (2°N) and 13 in Majuro (7°N).

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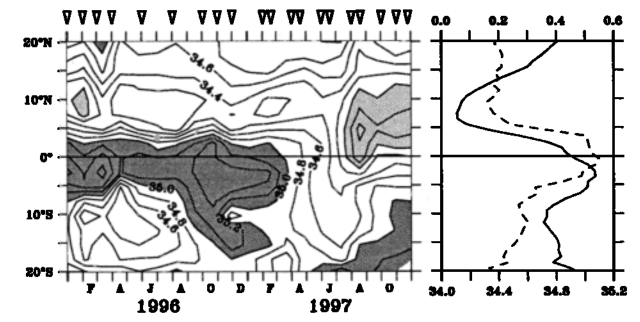

Figure 2. Left panel: Latitude-time evolution of SSS along the Fiji-Japan shipping track. Contour intervals are 0.2. Shaded areas indicate either values above 35 or below 34. The triangles on the top represent the departure dates of the 20 southward voyages. Right panel: 1996-97 mean (full line, bottom scale) and standard deviation (dashed line, upper scale) of SSS.

Data and processing

The SSS measurements derive from a ship of opportunity thermosalinograph network operated since 1992 from ORSTOM-Nouméa. The measurements, collected every 15 s, were obtained from SeaBird SBE-21 thermosalinograph instruments installed onboard two commercial vessels plying the shipping line Fiji-Japan (Figure 1). The SSS accuracy is about 0.01; details are given in *Hénin and Grelet* [1996]. The departure dates of the 20 voyages along the Fiji-Japan track during 1996-97 are reported on Figure 2; note that most 25°N-20°S voyages (lasting about 10 days) produced complete data sets, except during Oct. 1996 (8°N-2°N), Nov. 1996 (25°N-5°N, 20°S-8°S), Dec. 1996 (7°S-14°S), and Feb. 1997 (1°N-3°N). These gaps resulted either from instrumental failure or from a qualitative data validation procedure based on internal consistency and climatic limits.

The two vessels were also selected as part of the international Ship of Opportunity Program (SOP) for launching T7 eXpendable BathyThermogaph (XBT) probes every six hours. The T7-XBT provided temperature profiles from the surface down to 700 dbar with an accuracy of about 0.1°C. The XBT data validation relied on multiple standard deviation criteria. The temperature profiles were converted into 0/700 dbar DHA, using local mean Temperature-Salinity (TS) relation obtained from *Levitus et al.* [1994].

Gridded fields of TOPEX/Poseidon SLA (1°x1° latitude longitude by 10 days) were obtained via FTP (see the Acknowledgements). The estimated accuracy of SLA in this data base ranges from 2-4 cm; details are given in *Tapley et al.* [1994]. The SLA were sampled along the same shipping track as that of Figure 1.

For consistency, the time/space irregularly distributed SSS data, temperature profiles, and SLA data were all plotted on a regular grid using an objective interpolation scheme (Laplacian method; see *Delcroix and Hénin* [1991]) with a grid element size of 1° latitude by 1 month, neglecting the small zonal variations around the mean track between 2°N and 10°N. Both the 0/700 dbar DHA and SLA were computed relative to the January 1996 - November 1997 period.

Results

The latitude-time evolution of SSS along the track, as well as the 1996-97 average and its standard deviation (σ_s), are shown in Figure 2. The mean value exhibits the well-known SSS minima [*Delcroix et al.*, 1996]: one around 8°N ($SSS < 34.2$) associated with the ITCZ and the North Equatorial CounterCurrent (NECC), and the other around 12°S ($SSS < 34.8$) associated with the SPCZ and the South Equatorial CounterCurrent (SECC). At the equator, the value of 35 indicates that the eastern edge of the warm and fresh pool was located around 170°E on average during 1996-97, similar to the long-term mean [*Levitus et al.*, 1994]. The strongest variability ($\sigma_s > 0.3$) is trapped in the equatorial band, maximum at the equator ($\sigma_s = 0.55$), as observed from cruises along 165°E during 1984-94 [*Delcroix and Picaut*, 1998].

Away from the equatorial band, the SSS evolution exhibits a well-marked seasonal cycle in the ITCZ and SPCZ. There, the SSS minima occurred at the end of the summer season of each hemisphere, mainly in relation to the P seasonal cycle [*Delcroix and Hénin*, 1991]. In the equatorial band the SSS evolution is much more spectacular, and can be separated into three different time periods. Firstly, during 1996 (when the SOI was weakly positive indicating a La Niña-like period) the SSS was almost constant within 35.2-35.4, i.e. above the long-term mean by about 0.2. Secondly, from January 1997 (when the SOI switched from positive to negative indicating an El Niño signal) to August 1997, the SSS decreased sharply from 35 to below 33.8. This last value is the smallest monthly-averaged SSS observed in the studied area for more than 20 years, according to the 1973-95 SSS time series in *Delcroix* [1998]. Thirdly, during the remaining time period, the SSS remained almost constant (34.2), well below the long-term mean value (35), while the SOI indicated the persistence of El Niño at basin scale.

Let us now turn to a qualitative discussion of the SSS changes in the equatorial band. The 1996-97 mean sea-surface topography (Figure 3) reveals the meridional boundaries of the surface zonal geostrophic currents, and in particular the mean westward-flowing South Equatorial Current (SEC) in the equatorial band. During most of 1996, a period characterised by above-average SSS, the SLA presents a tendency for a negative curvature at the equator (the SLA at the equator is lower than the SLA on each side of the equator), indicating a stronger-than-average SEC. The presence of this westward flow in the surface layer during most of 1996 is confirmed by the 0°N-165°E TAO current measurements [*McPhaden*, 1993], and by the trajectories of drifting buoys in operation for the CLIVAR Surface Velocity Program [*Niiler et al.*, 1996]. (For conciseness, TAO- and SVP-derived measurements are not shown

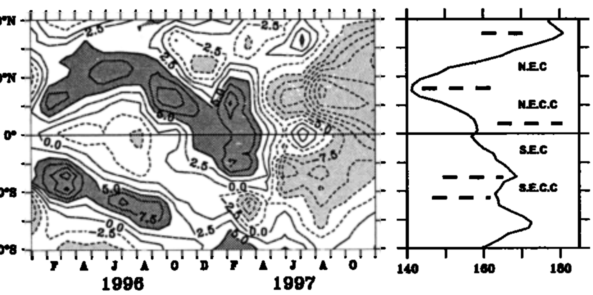

Figure 3. Left panel: Latitude-time evolution of the TOPEX/Poseidon derived sea level anomalies (re. Jan. 1996 - Nov. 1997) along the Fiji-Japan shipping track. Contour intervals are 2.5 cm. Shaded areas indicate either values above 5 or below -5 cm. Right panel: XBT-derived 1996-97 averaged 0/700 dbar dynamic height. Units are dyn cm. The surface zonal geostrophic currents referenced in the main text are indicated.

here; they can be found in the 1996-1997 monthly issues of the Climate Diagnostics Bulletin edited by the US Dept. of Commerce and/or at http://nic.fb4.noaa.gov). Furthermore, the vertical thermal structure averaged between April and August 1996 (Figure 4a) indicates the occurrence of an equatorial upwelling, with a clear rise of the 28°C isotherm from about 100 m at 5°N and 5°S to near-surface at the equator. This upwelling structure is reminiscent of a strong SEC and characteristic of a La Niña period at 170°E. Still, the precipitation (P) anomalies were below average as inferred from outgoing longwave radiation (see the Climate Diagnostics Bulletin). Hence, the above-average SSS is consistent with horizontal and vertical advection, which, given the mean horizontal and vertical salinity gradients (see *Delcroix and Picaut,* 1998), could conceivably bring relatively high salinity water from the east and from below, as well as with the rainfall deficit.

From January to August 1997, when the SSS decreased sharply by 1.6, the SLA (Figure 3) presents generally a tendency for positive curvature at the equator, and it is generally positive. This suggests geostrophic eastward flow anomalies as well as local downwelling. Indeed both the 0°N-165°E TAO current measurements and the drifting buoy trajectories, indicate strong near-surface eastward flows reaching as much as 60 cm/s, associated with recorded episodes of westerly winds of the order of 2-8 m/s. Furthermore, the vertical thermal structure in January-May 1997 (Figure 4b) is strikingly different from that of the previous period (Figure 4a), indicating a well-marked equatorial downwelling and a 140 m deep isothermal layer (T>28°C). This downwelling structure is consistent with eastward flows, positive SLA and downwelling Kelvin waves, and it is characteristic of the onset of El Niño in the western equatorial Pacific. Contrasting with 1996, the P anomalies were above-average in the first half of 1997. Hence, the observed SSS decrease appears consistent with both horizontal and vertical advection, likely bringing relatively low-salinity water from the west and suppressing the import of high salinity water from below, as well as with above-average precipitation.

From September 1997, when the SSS stayed almost constant (34.2), the SLA (Figure 3) decreased to reach -15 cm by November. At that times, the drifting buoy trajectories clearly indicate the occurrence of strong eastward flows in the near-surface layer, consistent with the quasi persistence of westerly winds at the 0°N-165°E mooring site. (Note that at the time of writing the 0°N-165°E TAO current measurements have not yet been recovered). The vertical thermal structure in the second half of 1997 changed drastically (Figure 4c), with a reduction of about 50 m of the thickness of the isothermal layer corresponding to the basin-scale zonal tilt of the thermocline detectable from the equatorial TAO moorings. Interestingly, by September 1997, the P anomalies shifted from positive to negative at 170°E, and the SST anomalies, which had remained nearly constant during the first half of 1997, started to cool (Figure 5). These conditions suggest that the almost-constant SSS during Sept.-Nov. 1997 could reflect the balance between eastward advection which would tend to lower SSS versus the combined effects of rainfall shortage, vertical mixing and evaporative cooling which would tend to increase the SSS.

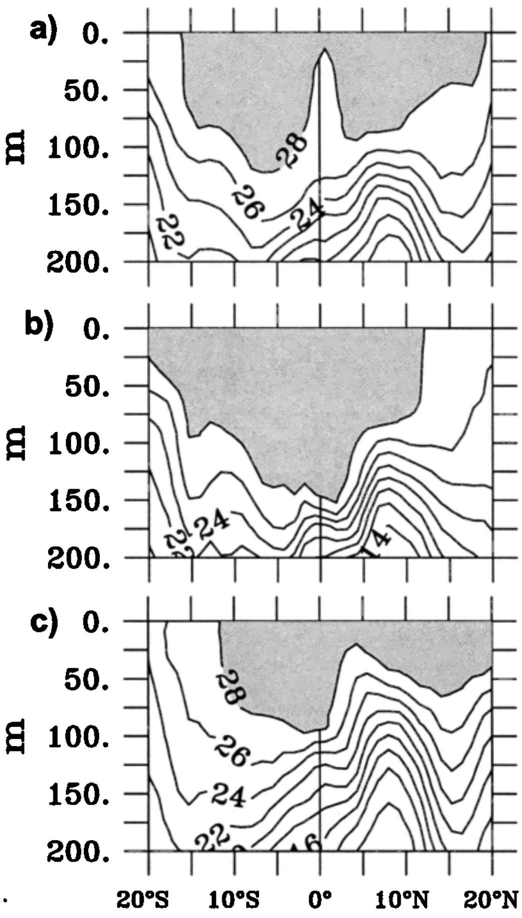

Figure 4. Latitude-depth distribution of the thermal structures along the Fiji-Japan shipping track, averaged over: (a) Apr. - Aug. 1996, (b) Jan. - May 1997, and (c) July - Nov. 1997. Contour intervals are 2°C, and shaded areas denote temperatures warmer than 28°C.

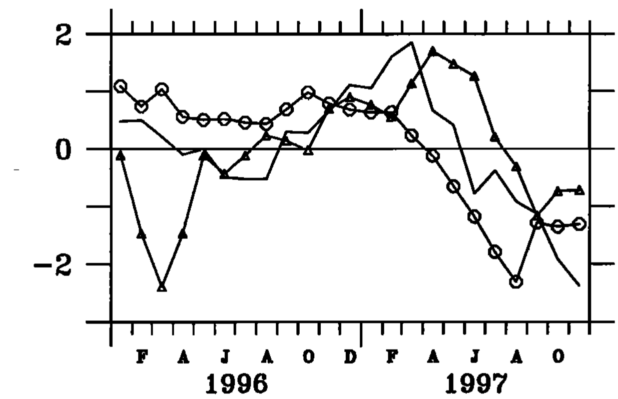

Figure 5. Magnitude of the 5°N-5°S averaged TOPEX/Poseidon derived sea level anomaly (full line), XBT-derived SST anomaly (triangles), and thermosalinograph-derived SSS anomaly (circles). The anomalies are relative to the Jan. 1996 - Nov. 1997 period, and they are normalised by their respective standard deviations (5.2 cm for sea level, 0.33°C for SST, and 0.46 for SSS). Note that the SSS signal discriminates the 1996 La Niña from the 1997 El Niño periods more clearly than the SST and sea level signals.

Conclusion and discussion

To conclude, we have shown that SSS experienced drastic changes in the warm pool region, with peak to peak variations in the equatorial band of as much as 1.6 between the 1996 La Niña and the 1997 El Niño. Assuming that these SSS changes were representative of the upper 50 m, they would correspond to a change of 6 cm in sea level, all other factors being the same, a value which is of the same order of magnitude as the standard deviation of SLA derived from TOPEX/Poseidon during 1996-97 (5.2 cm; see Figure 5). The SSS changes were found qualitatively consistent with horizontal and vertical advection, as well as with precipitation, vertical mixing and evaporative cooling. Although instructive, our qualitative analysis admittedly remains to be quantitatively assessed, possibly via model results in the absence of suitable in situ measurements, provided that salinity changes would be reproduced correctly in models.

One interesting question is the potential effects of the notable observed SSS changes, as presently shown, regarding the quality of ENSO prediction in numerical models assimilating temperature and/or altimeter-derived sea level data only [*Ji et al.*, 1995]. As discussed by *Acero-Schertzer et al.* [1997], the lack of salinity control in this type of models results in major discrepancies between near-surface modelled and observed currents. Such a failure is especially relevant in the western equatorial Pacific where there is a strong ENSO-related near-surface salinity signal, and where zonal advection is of main importance for ENSO mechanisms. With this contention in mind, it is clear that methods should be developed to assimilate SSS data in prediction models. Expansion of our SOP thermosalinograph network, with real-time transmission of the measurements, is currently in progress to partly fulfil this requirement.

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