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Large-Scale Current and Thermohaline Structures Along 156°E During the COARE Intensive Observation Period

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Abstract. From December 1992 to February 1993, 18 meridional sections of temperature, salinity, and current were collected along 156°E, from 5°S to 5°N, during the Intensive Observation Period of the Coupled Ocean-Atmosphere Response Experiment. The average conditions were characteristic of the ongoing El Niño event, with a relatively shallow thermocline and fresh surface waters. Alternating westerly and easterly wind forcing was observed, and the warm surface layer (the "Warm Pool") responded in a time scale of a few days by corresponding alternating flows; the equatorial current system was less affected at depth. The upper-layer oceanic temperature variability involved several mechanisms, including surface cooling by evaporation during westerly winds and entrainment from the thermocline.

Introduction

An incomplete description of moisture, heat and momentum fluxes between the atmosphere and the ocean in the Warm Pool regions of the tropics, and especially in the western Pacific Ocean, has resulted in failures in simulating the state and evolution of the coupled ocean-atmosphere system. To gain greater insights into the nature of this interaction, the TOGA Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) was initiated [*Webster and Lukas,* 1992]. At the heart of COARE, a 4-month Intensive Observation Period (IOP) was planned. In order to provide the large-scale context of current and thermohaline structure variability for the period, the COARE-POI cruise was organized by the SURTROPAC Group, as its contribution to the COARE IOP. The purpose of this note is to present the first results from high horizontal resolution upper ocean temperature, salinity and current data collected during that cruise.

Data and processing

The COARE-POI cruise was carried out onboard R/V Le Noroit, and produced 18 three-day long meridional sections of current, temperature and salinity measurements along 156°E, from 5°S to 5°N, collected from December 7, 1992 to February 24, 1993. Current profiles were continuously recorded along the ship track with a vessel-mounted 150 kHz ADCP. Velocity shear profiles in 8 m bins from 16 to 400 m depth were averaged every 5 min., and absolute water velocities computed from filtered GPS navigation. A Sea-Bird SBE-9 CTD was used to acquire 0-1000 m casts every 0.5 degree of latitude during the first 5 sections, and every degree during the 18th section. For the other 12 sections, a SeaSoar (a towed undulating vehicle) delivered continuous temperature and salinity data from the surface to 200 or 300 m. Surface meteorological measurements at 3-hour intervals (synoptic times) were also gathered routinely.

Accuracy of velocity, temperature and salinity data is estimated at 5 cm s^{-1}, 0.005°C and 0.005 psu, respectively. More details on data collection and processing can be found in the cruise report [*Delcroix et al.*, 1993].

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Mean structures along 156°E

Figure 1 presents vertical sections of temperature and salinity, averaged over the 18 sections, and gridded every 1/4 degree of latitude and every 5 m of depth. The surface layer in this region was characterized by a Warm Pool layer of high temperature (≥ 28°C) and low salinity (≤ 34.5 psu). The average thickness of this layer over 5°S-5°N, defined as the depth of the 28°C isotherm, was 60 m, with a maximum of 75 m at the equator. Average near-surface temperatures exceeded 29°C between 5°S and 2°30'N. A meridional salinity gradient (negative northward) was noticeable, with a salinity minimum around 2°N. The vertical stratification also decreased northward. The standard deviation of temperature in the surface layer was of the order of 0.5°C, except south of 4°S, where it reached 1°C. Below the 28°C isotherm, the vertical temperature gradient increased strongly and exhibited the typical features of the thermocline in the western equatorial Pacific as described in *Delcroix et al.*, [1992] and *Toole et al.*, [1988]. Within the thermocline, the southern hemisphere subtropical salinity maximum extended from 5°S to near the equator, reaching 35.5 psu south of 2°S, and centered roughly at the depth of the 21-22°C isotherms. At slightly shallower levels, high salinity waters extended across the Equator to 3-4°N, above a salinity minimum originating from the Northern Hemisphere [*Tsuchiya et al., 1989*].

When compared to the climatology of *Levitus* [1982], the 4°S-4°N mean temperature profiles showed that water temperatures below the surface homogeneous layer were colder than usual for a given depth. In terms of vertical displacements, the 20-28°C isotherms were 10-40 m shallower than those derived from Levitus. The average surface salinities from COARE-POI were everywhere below 34.3 psu, and below 34.0 psu between the equator and 3°N. These values were a few tenths of a psu lower than those of the Levitus climatology, and closer to the discrete meas-

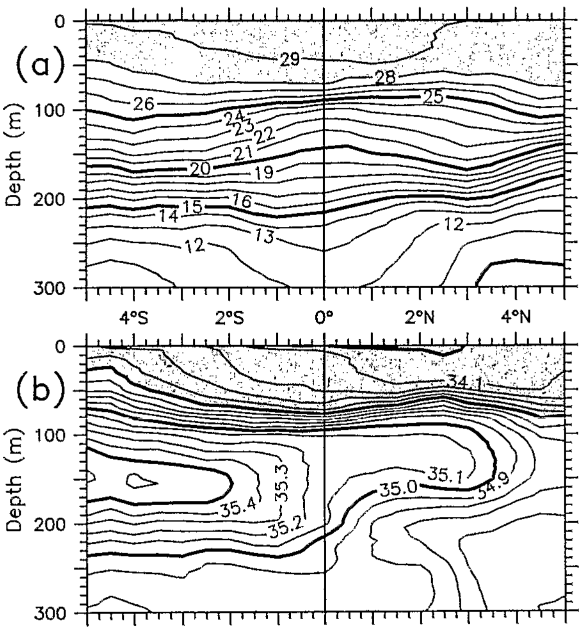

Figure 1. December 1992 - February 1993 average sections at 156°E of (a) temperature and (b) salinity, shaded above 28°C and below 34.5 psu, respectively. Isotherms and isohalines are drawn every 1°C and 0.1 psu, respectively.

urements from the WEPOCS 2 cruise in February 1986 after a strong westerly wind episode [*Tsuchiya et al.*, 1989]. Our measurements in December 1992 - February 1993 were carried out during a period of abnormally shallow thermocline, with a relatively thin and low-salinity Warm Pool. These features were characteristic of the ongoing El Niño conditions, as shown by previous studies [*Kessler and Taft*, 1987; *Delcroix and Hénin*, 1991].

The average zonal and meridional velocity sections are shown in Figure 2. The apparent weakness of the flow was caused by the averaging of highly variable currents (see next section). At the surface, the standard deviation was in fact larger than the mean. In the surface layer corresponding to the Warm Pool, the averaged zonal flow was mostly eastward south of the equator, and weakly westward in the northern hemisphere. The South Equatorial Current (SEC) was almost entirely confined to the upper thermocline, between 60 and 150 m, with a maximum velocity close to 30 cm s^{-1} around 1°N and 100m. The SEC was flanked on each side by the North and South Equatorial Counter-currents (NECC, SECC) of comparable strength. While the NECC core was also located within the upper thermocline, the SECC maximum was found at the surface, around 4°S. South of this latitude, the high shear zone was probably associated with circulation patterns around the Solomon Islands chain. The Equatorial Undercurrent (EUC) was also relatively weak, centered around 1°S; its core was below the 20°C isotherm, between 150 and 220 m. The South and North Subsurface Counter-currents (SSCC, NSCC) were symmetrical in strength and position, at 3°S and 3°N respectively. Average meridional velocities were weaker than the zonal flow. In the Warm Pool, the currents had a small northward component, except for the SECC which tended to follow the Solomon Islands chain. In the core of the SEC and the NECC the meridional component was mostly to the south. The EUC was slightly convergent, with a meridional flow of a few cm s^{-1} of opposite sign on each side of the equator.

In addition to the low velocity and transport caused by averaging, this current distribution had some substantial differences with previous measurements, mostly in the layers above the EUC. During the WEPOCS 2 cruise (1986), the flow at 155°E was generally westward above 150 m, except for the NECC, which was confined north of 4°N. At depth, the NECC during WEPOCS 2 was separated from the EUC [*Tsuchiya et al.*, 1989]. The long-term mean at 165°E [*Delcroix et al.*, 1992] also showed a constant SEC from the surface down to the EUC. At 165°E as well as at 156°E, the average NECC, EUC and subsurface counter-currents were similar in shape and position, but the SECC at 165°E was found further south, at 8°S.

Oceanic variability from December 1992 to February 1993

The vertical structure has been separated into three layers: the Warm Pool layer (0-60 m), was characterized by high temperature, low salinity, and high flow variability including current reversals; below, in the upper thermocline, and above the 20°C isotherm (about 150 m depth), the temperature was slightly lower than normal, and westward flow dominated around the equator (SEC); below 150 m, temperatures as well as zonal currents stayed closer to their long-term means.

Local wind-stress and current response

Wind data from moorings show that westerly winds had been present at 156°E since October with occasional westerly wind bursts (WWB) [*McPhaden*, 1993]. Figure 3 presents time-latitude plots of wind pseudo-stress and depth-averaged currents for each of the three layers defined above. Although the cruise sampling does not allow an exact spatio-temporal description of the wind and current fields, major patterns are clearly evident. In early December, light winds prevailed (Figure 3a). The strength of the wind increased with time and reached its maximum (daily

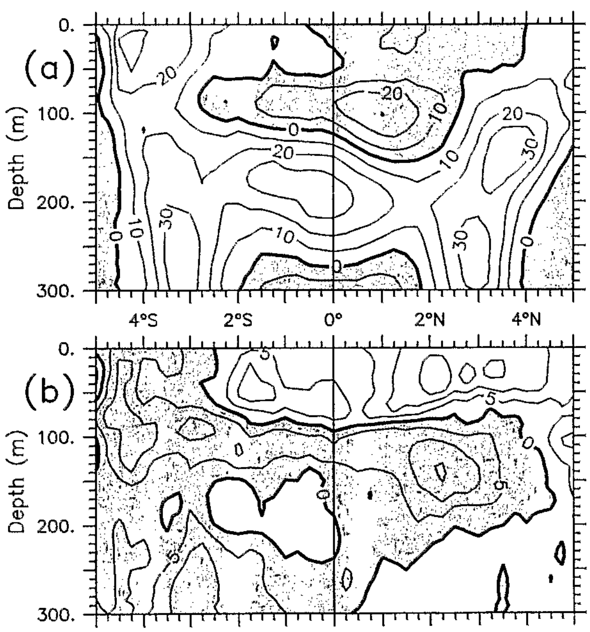

Figure 2. December 1992 - February 1993 average sections at 156°E of (a) zonal and (b) meridional ADCP-measured velocities. Isotachs are drawn every 10 (a) or 5 cm s^{-1} (b); negative westward and southward components are shaded.

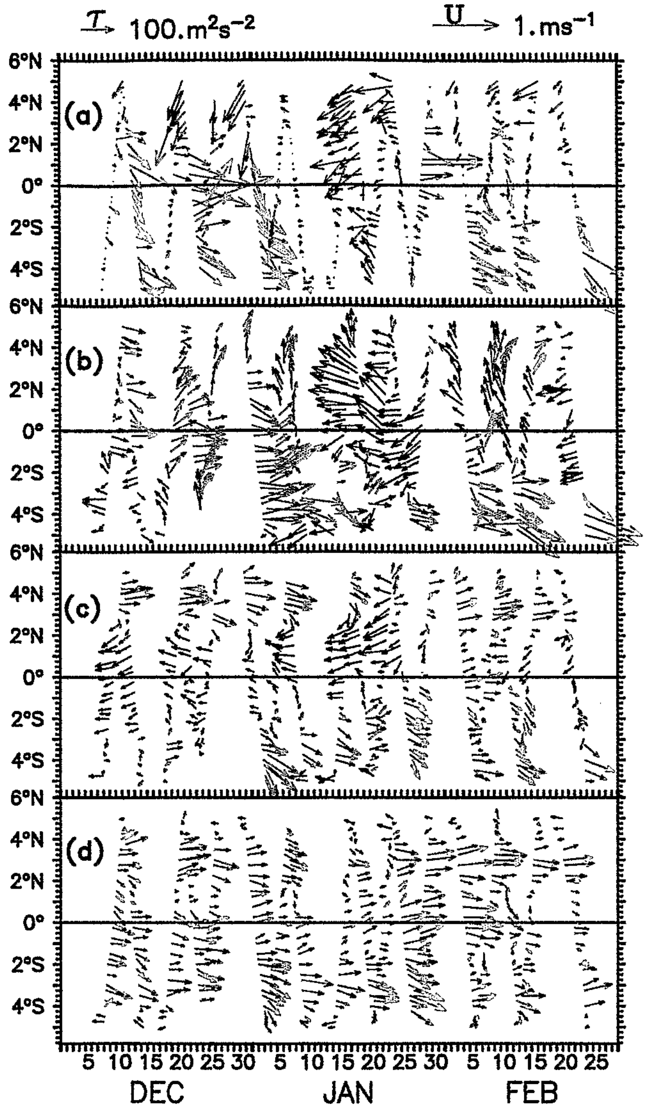

Figure 3. Time-latitude plots at 156°E, along the ship track, from December 1992 to February 1993 of (a) wind pseudo-stress and current velocity vectors averaged for three depth layers, (b) <16-60m> , (c) <60-150m> , and (d) <150-280m>. Vector scales are shown on top; wind pseudo-stress vectors with an eastward (westward) component are colored in purple (green); current vectors with an eastward (westward) component are colored in red (blue).

means ≥ 8 m s^{-1}) between December 22 and 26, while becoming more westerly. In the first days of January, strong north-westerlies still prevailed south of 2°N, and a return of the trade winds was observed further north. After some calm days, strong trades returned along the whole section from January 13 to 26, especially in the northern hemisphere. A second episode of westerly winds followed, comparable in strength to the previous one, but centered around 1°N. Moderate easterly and westerly winds then alternated north of the equator until the end of February. South of 1°S north-westerlies developed and strengthened in conjunction with the formation of tropical cyclones in the Coral Sea: "Oliver" in early February and "Polly" at the end of the same month.

In the surface layer (Figure 3b), a westward flow was present south of 2°S until December 20, while weak eastward flows dominated to the north. From December 12 on, a quasi-symmetrical eastward jet developed around the equator, and reached a maximum speed of 60 cm s^{-1} on December 20-25, extending from about 2°S to 2°N. This eastward flow extended progressively to the whole 5°S-5°N section in the first days of January with a strong asymmetry toward the south. By January 10 the flow had entirely reversed, except south of 3°S. A maximum westward current was observed around January 18 at 2-3°N, with speeds in excess of 1 m s^{-1}. Thereafter, currents became strongly meridional in the northern hemisphere, until mid-February. South of the equator, a south-eastward flow increased at the same time and moved away to the south.

It is remarkable that the surface flows responded to varying wind forcing on a time-scale of a few days. Changes from westerly to easterly stresses were generally immediately followed by corresponding changes in the flow. In particular, the December WWB induced an eastward Yoshida jet [*Moore and Philander,* 1977], transporting about 12 Sv (1 Sv = 10^6 m^3 s^{-1}) around December 22. It should be noted that previously observed occurrences of WWBs had led to a stronger eastward transport (≥ 20 Sv), as at the end of 1989 [*McPhaden et al.*, 1992]. The return of strong easterlies in early January was followed by a strong westward current. The second westerly wind episode did not affect surface circulation as much as the first one. The lower strength and duration of westerly wind stress north of the equator may explain this difference. Poleward of 1-2° of latitude, currents had a tendency to run to the right or left of the wind stress, depending on the hemisphere, as a consequence of Ekman dynamics.

Below 60 m, in the upper thermocline layer (60-150 m, Figure 3c), the currents were still partially affected by surface forcing but were more stable. Therefore they can be more easily related to the classical equatorial currents. The SEC was almost always present, and accelerated during the strong easterlies. As previously observed along 165°E by *Delcroix et al.* [1993], the SEC accelerated during WWBs, but this acceleration is not apparent on Figure 3 because of vertical averaging. The weakest flow occurred from the end of January to early February and eventually reversed. At the same time, the subsurface eastward currents (EUC, SSCC, NSCC) were at their shallowest, and the SEC proper was restricted to shallow layers north of the equator. The increase of these subsurface eastward currents did not seem to be directly related to local forcing. The NECC was strong and reversed only briefly around January 22, after more than a week of easterly wind stress. South of the equator, the SECC was only affected by strong wind events occurring in early January, and in February by the cyclonic wind circulation. In the deepest layer (150-280m, Figure 3d), the EUC and the subsurface counter-currents were much more stable. Some variability existed, but did not appear to be related to wind forcing, except for the NSCC, which weakened in mid-January like the NECC.

Temperature variability of the equatorial surface layer

An indication of the mechanisms producing variations in near-surface temperature can be estimated from the COARE-POI cruise. Figure 4 presents 1°S-1°N averages, for each section, of wind speed, sea-surface temperature (SST), and the time-depth temperature distribution in the first 100m. At the beginning of December, the surface layer was stratified, with a temperature difference of 0.8°C between the surface and 70 m (depth of the 29°C isotherm and top of the thermocline). As the WWB developed, the SST decreased from 29.8 to 29.2°C and the surface layer became well mixed down to 70 m. At that depth, temperature had remained constant, suggesting that cooling by vertical

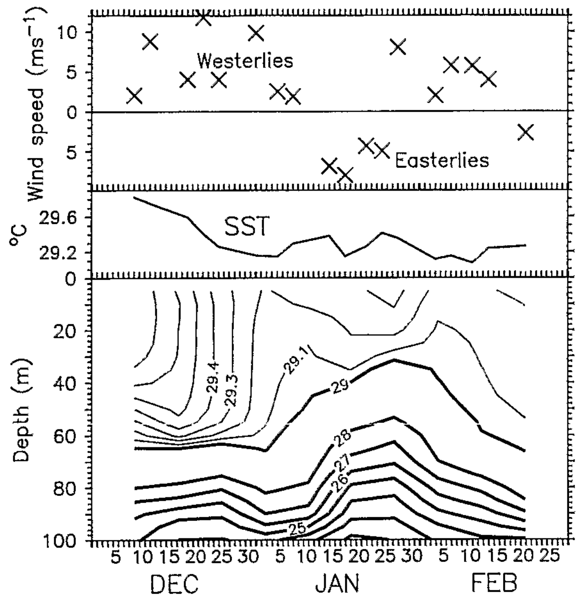

Figure 4. December 1992 - February 1993, 1°S-1°N averages along 156°E. From top to bottom: wind speed (positive downward easterlies), SST, temperature distribution in the 0-100 m layer (isolines every 0.1°C above 29°C and 1°C below).

entrainment from below was negligible. Evaporative cooling and vertical mixing have, in previous studies, been shown to be important in this region [*Meyers et al.*, 1986; *McPhaden*, 1990]. In early January, the SST rose by 0.25°C and the surface layer started to re-stratify in conjunction with a sharp decrease of the wind stress. As soon as the easterlies started to increase, the entire thermocline rose sharply and the 29°C isotherm reached 30 m, which might reflect large-scale dynamics [*Busalacchi et al.*, 1993] as well as local Ekman divergence. At the end of January, upon the return of westerlies, the SST decreased by 0.3°C in two weeks and the surface layer temperature again became more homogeneous, while the thermocline deepened, probably because of local Ekman convergence. The 29°C isotherm went back down to 70 m by mid-February.

Conclusions

The COARE-POI cruise has provided the large-scale context of the COARE Intensive Observation Period. El Niño conditions were still in effect, and the thermocline associated with the Warm Pool was found to be shallower than normal in the area. Alternating phases of westerly and easterly winds were experienced, including a strong westerly wind burst at the end of December 1992, centered on the equator. In the Warm Pool, near-surface zonal flows were found to react very rapidly (on the order of three days) to changes in the wind stress. In December 1992, strong westerly winds and surface eastward currents were associated with a sharp decrease in the SST and thickening of the surface isothermal layer. Evaporative cooling and mixing of a previously stratified upper layer appear to be responsible for these thermal variations. In January and February 1993, during easterly and westerly winds, entrainment from below the surface layer also seem to have been important.

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