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VARIABILITY OF UPPER OCEAN WATER MASSES AND TRANSPORTS IN THE WESTERN EQUATORIAL PACIFIC DURING THE TOGA PERIOD

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INTRODUCTION During the latter half of the TOGA observing period, attention was focused on the western tropical Pacific, this despite the fact that ENSO-related SST anomalies are maximum to the east. Motivation for study of the western Pacific derived from suggestions of strong coupling between the atmosphere and ocean when SST approached 30°C. The TOGA-COARE program in particular was initiated to document processes that control SST and the spatial distribution of the Warm Pool. The present note addresses these objectives by discussing the mean and time-varying temperature (T), salinity (S) and zonal current (U) structures observed in the western equatorial Pacific during the 1984-1992 period. This period encompasses two El Niño surrounding a strong La Niña (see the SOI in Figure 1).

THE DATA Six independent research programs conducted physical oceanographic measurement programs along 165°E during the TOGA period. Together these provided a series of 39 oceanographic sections along 165°E between 20°S-10°N (Figure 1). Temperature, salinity and current sections were obtained using standard CTD, PCM and ADCP instruments. Details on data processing can be found in Delcroix et al. (1992).

MEAN (1984-92) Mean sections of T, S, and U were derived, along with the corresponding distributions of standard deviation, by averaging the data from these 39 cruises on pressure surfaces, Figure 2. Previously, mean sections based on a subset of these sections were discussed by Delcroix et al. (1987, 1992) (averages also done on pressure surfaces) and Gouriou and Toole (1993) (who formed averages on density surfaces).

Temperature. The Warm Pool at 165°E (T>28°C) extends on average from 15°S to north of 10°N; maximum thickness of approximately 100 dbar occurs at 4°S. SST is above 29°C between 10°S and 6°N. A sharply-defined thermocline spanning temperatures between 25°C and 15°C lies below the Warm Pool, with ridges and troughs reflecting the zonal geostrophic upper-ocean currents. Thermocline spreading associated with the EUC is well marked at the equator.

Salinity. Low salinity water (S<34.5 psu) near the surface is found north of 2°N and between 6°S and 11°S; both are associated with bands of heavy rainfall: the ITCZ and SPCZ respectively. The wind curl associated with these features give rise to the north and south equatorial countercurrents about these same latitudes. The average distribution exhibits a halocline around 50 dbar, which is significantly shallower than the thermocline. This is the "barrier layer" discussed by Lukas and Lindström, 1991. Below the halocline, a tongue of high salinity south Pacific tropical water (Tsuchiya et al., 1989) about 160 dbar is seen extending north and crossing the equator. It's northern hemisphere counterpart is confined north of 10°N. North of the equator the low-salinity north Pacific intermediate water is seen below 150 dbar (Reid, 1965).

Zonal current. The main flows characterising the western tropical Pacific circulation (Magnier et al., 1973) are clearly present at 165°E: at the surface the NEC is found north of 9°N, the NECC from 1°N to 9°N, and the SEC from 1°S to 15°S separated into 2 bands by the SECC (6°S-10°S). Below the surface are located the EUC centred on the equator at 190 dbar, contiguous with the NSCC and SSCC centred around 250 dbar at ± 3° ,latitude. The EIC is present below the EUC.

VARIABILITY The standard deviation of T (Figure 2) is maximum (>2°C) in the equatorial region (10°N-10°S) within the thermocline (100-230 dbar). This signal is caused by isotherm vertical displacements linked to ENSO variability as well as westerly wind bursts (WWB). The standard deviation of S is above 0.2 psu in the upper 100 dbar. The equatorial maximum is associated with the reversals of the zonal currents that occur during ENSO (advecting the zonal surface salinity gradient past 165°E) and upwelling events that occur during La Niña. A second maximum (>0.3 psu; 18°S-10°S) is related to vertical heaving of the halocline. The standard deviation of U is above 20 cm/s between 10°N-10°S, associated with meridional displacements of the currents (NECC, SECC, southern branch of the SEC) and/or changes in their intensity. The maximum of zonal velocity variability is at the surface centred about the equator (50 cm/s). This extreme appears caused by equatorial wave signatures during ENSO (current reversals) and westerly wind burst effects.

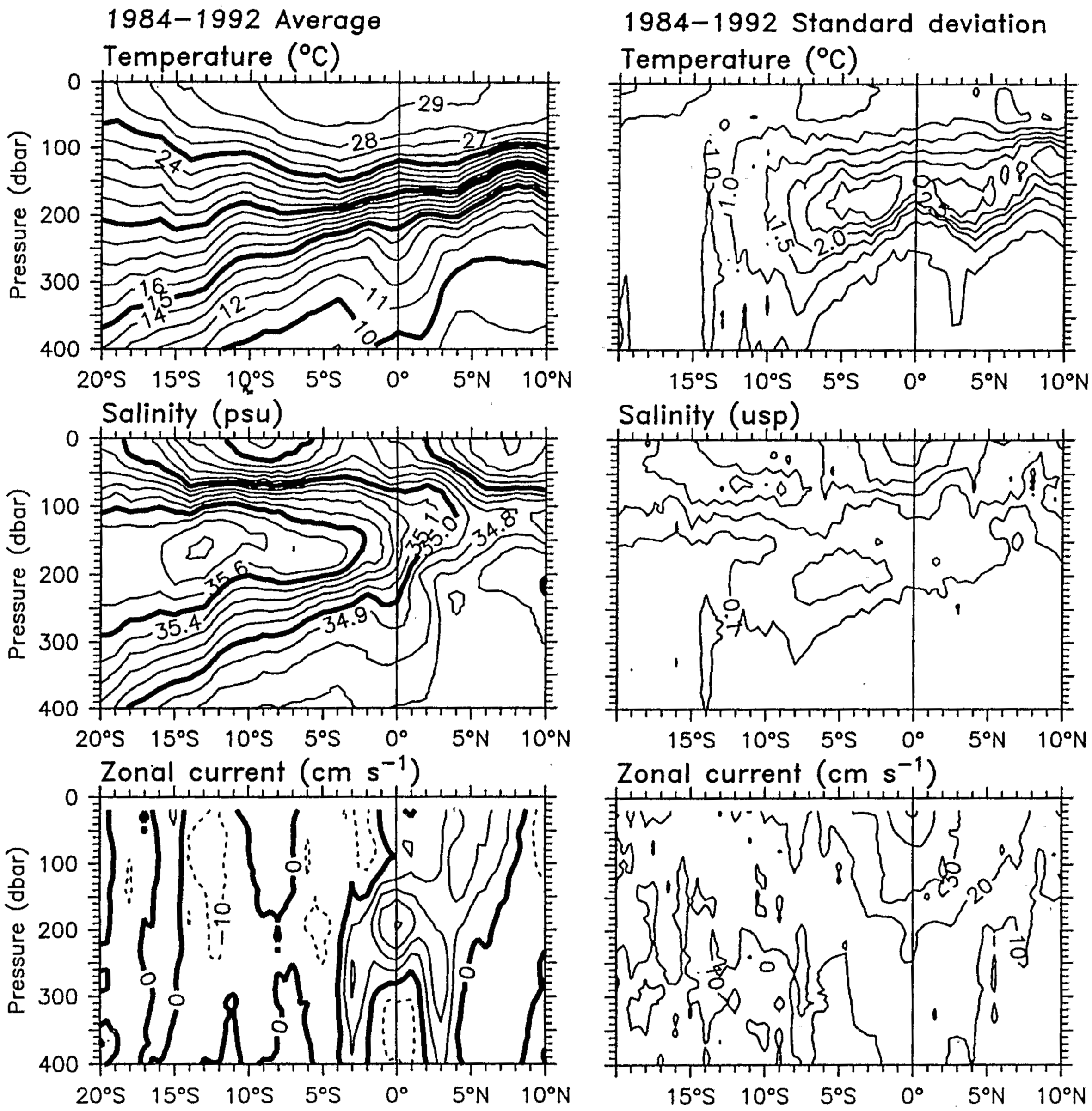

Figure 2- <1984-1992> averaged section of temperature, salinity, and zonal current at 165°E, together with their corresponding standard deviations . Positive currents are eastward.

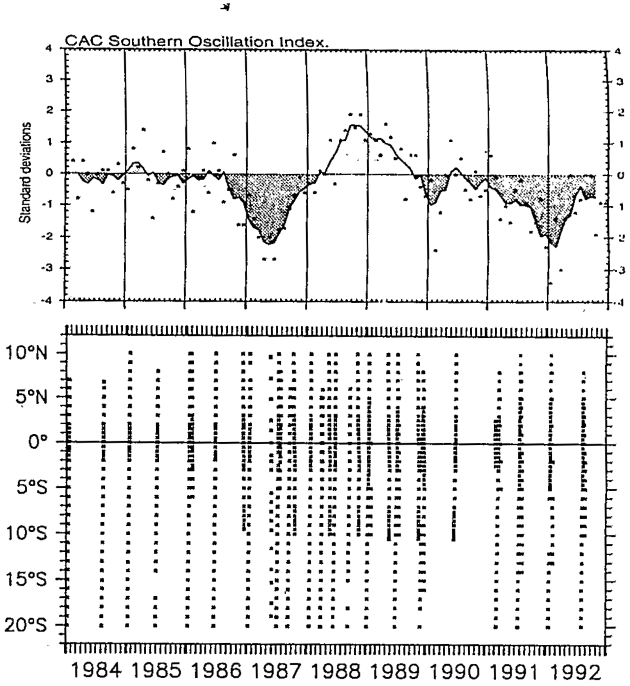

Figure 1- (Top) 5-month running mean of the Southern Oscillation Index. (Bottom) Time-latitude plots of the hydrographic stations near 165°E.

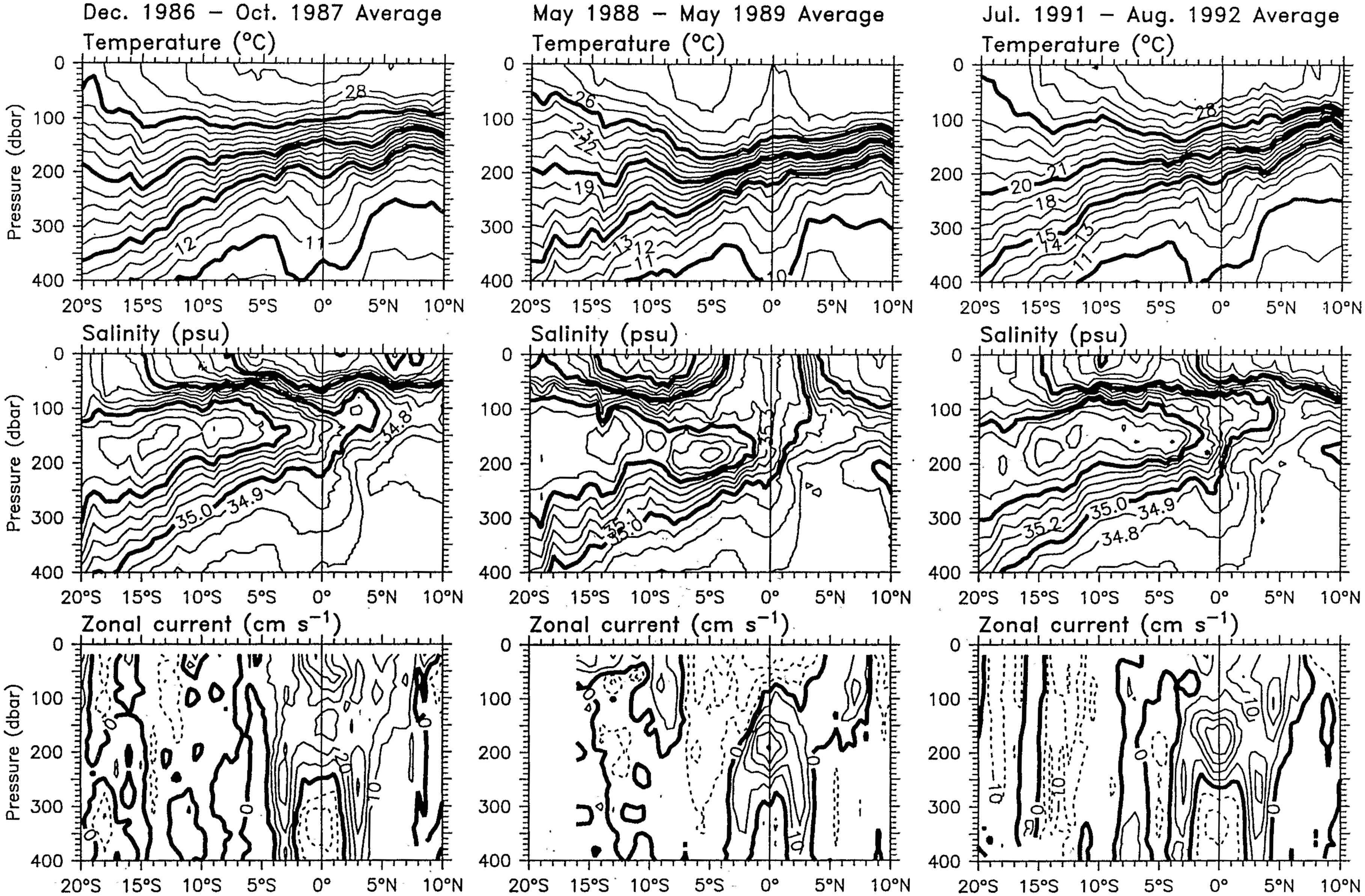

Figure 3- Section of temperature, salinity, and zonal current at 165°E averaged during (left panels) Dec. 86 - Oct. 87 (the 1986-87 El Niño), (middle panels) May 88 - May 89 (the 1988-89 La Niña), and (right panels) July 91 - Aug. 92 (the 1991-92 El Niño). Units as in Figure 2.

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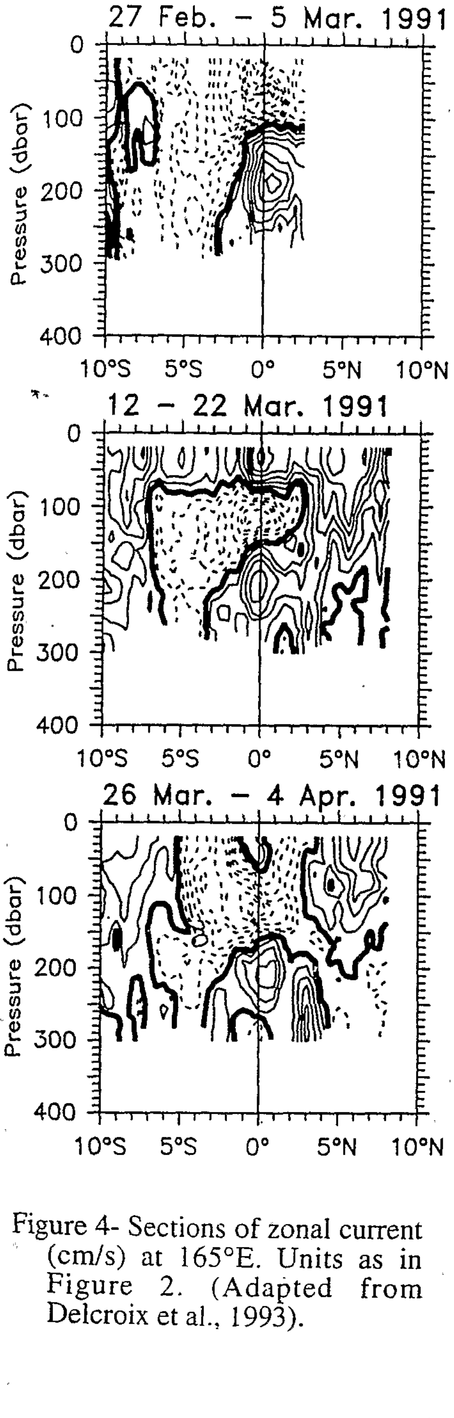

Figure 4- Sections of zonal current (cm/s) at 165°E. Units as in Figure 2. (Adapted from Delcroix et al., 1993).

Characteristics of El Niño and La Niña. Based on the SOI, 3 periods of approximately 1-year duration are chosen to characterise the 1986-87 El Niño (Dec. 86 - Oct. 87), the 1988-89 La Niña (May 88 - May 89), and the 1991-92 El Niño (July 91 - Aug. 92). Figure 3 shows the averages of sections available over each of these three periods.

During Los Niños, the equatorial area at 165°E is characterised by low salinity surface waters. During La Niña, equatorial upwelling is pronounced and the 28°C isotherm and high salinity water (35.0 - 35.2 psu) outcrop at the equator (Figure 3; see also Sprintall and McPhaden, 1994). Mean currents during the two El Niño periods were strongly eastward over the latitude range 8°N-8°S, not just near the equator. In sharp contrast with El Niño conditions, a strong SEC was present between 7°S and 5°N during La Niña. The weakness of the EUC during the 1986-87 El Niño reflects its disappearance during part of the period (McPhaden et al., 1990; Delcroix et al., 1992).

Both local and remote forcing appear responsible for changes in thermocline depth and upper layer zonal currents at 165°E. During Los Niños, zonal winds at 165°E were on average westerly at and south of the equator. This contrasts with La Niña conditions in which unusually strong easterlies are typical in the interval 10°N-10°S (not shown here). Meridional dynamic height structures along 165°E and basin-wide altimetric data proved invaluable for documenting remotely forced variability, identified in the form of first baroclinic downwelling (upwelling) Kelvin waves and first meridional mode upwelling (downwelling) Rossby waves during El Niño (La Niña) episodes (Delcroix et al., 1992, 1994).

Westerly wind burst signature. High-frequency variability at 165°E is superimposed on ENSO-related changes, in particular that related to WWB: prominent players in the wind variability over the western Pacific warm pool. Local effects of WWB on current structures have been documented by Hisard et al. (1970) and McPhaden et al. (1988, 1990). Here, following Delcroix et al. (1993), we describe WWB effects during February - April 1991, using ADCP measurements from 3 cruises along 165°E, separated by 10-20 days.

The classical picture of the zonal circulation field was observed on the first section (Figure 4) which crossed the equator 1-2 days after the beginning of a WWB. Within 1-2 weeks after westerlies commenced, eastward and westward jets developed between about 2°N-2°S in the upper and lower halves of the temperature mixed layer. During the third section, after 8 days of easterlies, the SEC was re-established from 5°S to 3°N, except at the equator where a small patch of eastward flow persisted. Changes in zonal transport within 250 km of the equator above the main thermocline from one cruise to the next were approximately 30 Sv, illustrating how fast the zonal transport can be modified in the vicinity of the equator. These observations are in agreement with conceptual models of the equatorial mixed layer (e.g. Gill, 1971).

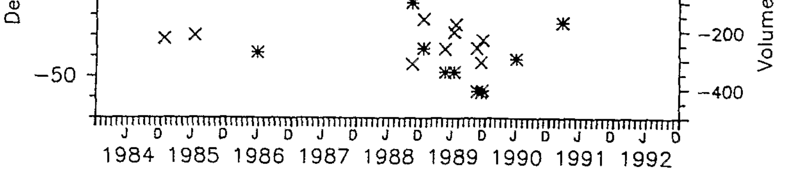

Figure 5- (Crosses) <3°N-3°S> averaged 25°C isotherm depth anomaly at 165°E. (Stars) Time integral of 3°N-3°S upper ocean (T>25°C) transport anomaly across 165°E. Each plot is relative to the 1984-1992 period (the mean 25°C isotherm depth is 127 m).

DISCUSSION AND CONCLUSION

The Warm Pool thickness at 165°E, represented by the depth of the 25°C isotherm, experienced striking variations during the TOGA period. Within 3°N-3°S the layer expanded and contracted by about 100 m between the Los Niños and La Niña, a 80% change about its average thickness (Figure 5). Changes in the zonal advection of the layer past 165°E was shown to significantly influence the volume of warm surface waters in the western equatorial Pacific, during 1986-1988 (Delcroix et al., 1992). In Figure 5, this analysis is extended with the addition of 6 more years of measurements. Specifically, Figure 5 compares the above 3°N-3°S averaged 25°C isotherm depth anomaly at 165°E with the time integral of the 3°N-3°S upper ocean (T>25°C) transport anomalies across 165°E (relative to the 1984-1992 period). Despite the irregular cruise sampling, potential for aliasing and ill-defined temporal interpolation, the agreement between Warm Pool thickness and time-integrated transport strongly suggests that warm water volume variations of the western Pacific during 1984-1992 are in large part controlled by zonal transport across 165°E. During Los Niños, an eastward expansion of warm water takes place from the western Pacific to the central Pacific causing the Pool to thin. During La Niña, surface waters are restored to the western Pacific by anomalously strong westward flows.

In hindsight, the collection of 39 meridional trans-equatorial sections at 165°E during TOGA was a massive undertaking. The reward of that effort is a remarkable picture of the mean circulation and its variability in the western equatorial Pacific Ocean. Most striking perhaps is that variability: at both low frequency, related to ENSO, and at high frequency, associated with WWB. Importantly, the observed zonal current changes are comparable to the "mean" currents. These changes reflect both direct wind forcing and remotely forced long equatorial waves. Circulation changes alter the spatial distribution of the warm SST (McPhaden and Picaut, 1990; Picaut and Delcroix, 1995) and chiefly govern the volume of warm waters in the western equatorial Pacific (Delcroix et al., 1992; and Figure 5). The ability of models to reproduce the observed T, S, and U changes at 165°E and the associated modification of SST and warm water volume represents a stringent test of their capability.

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