Interannual sea surface salinity and temperature changes in the western Pacific warm pool during 1992–2000

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[1] Sea surface salinity (SSS) and sea surface temperature (SST) in the western Pacific warm pool (130°–180°E; 10°N–10°S) are analyzed for the period 1992–2000 taking advantage of complementary data from the ship of opportunity program and the Tropical Atmosphere-Ocean (TAO)-Triangle Trans-Ocean Buoy Network (TRITON) array of moored buoys. Covariability of these variables with surface wind stress, surface zonal currents, evaporation, precipitation, and barrier layer thickness is also examined. These fields all go through large oscillations related to the El Niño Southern Oscillation (ENSO) cycle, most notably during the record breaking 1997–1998 El Niño and subsequent strong 1998–2000 La Niña. East of about 160°E, during El Niño, precipitation minus evaporation increases in the equatorial band, in conjunction with anomalous increases in westerly winds, eastward surface currents, SST, and decreases in SSS. Opposite tendencies are evident during La Niña. Peak to peak 2°N–2°S averaged variations reached as much as 1.2 m s⁻¹ for zonal currents and 1.5 practical salinity units (psu) for SSS. West of about 160°E, SST cools during El Niño and warms during La Niña, opposite to what occurs further east. To understand these SST tendencies west of 160°E, a proxy indicator for barrier layer formation is developed in terms of changes in the zonal gradient of SSS (∂SSS/∂x). Zonal SSS gradients have been shown in modeling studies to be related to barrier layer formation via subduction driven by converging zonal currents in the vicinity of the salinity front at the eastern edge of the warm pool. Correlation between changes in ∂SSS/∂x and changes in SST a few degrees longitude to the west is significantly nonzero, consistent with the idea that increased barrier layer thickness is related to warmer SSTs during periods of westward surface flow associated with La Niña, and vice versa during El Niño. Direct evidence of barrier layer thickness variations in support of this hypothesis is also presented. INDEX TERMS: 4231 Oceanography: General: Equatorial oceanography; 4522 Oceanography: Physical: El Niño; 4528 Oceanography: Physical: Fronts and jets


1. Introduction

[2] The distribution of salt in the global ocean and its variability on different timescales are of great importance in understanding the ocean’s role in the Earth’s climate [Sverdrup et al., 1942]. Notable in this regard are near-surface salinity changes in the western tropical Pacific, which can influence air-sea interactions involved in the El Niño Southern Oscillation (ENSO) events [see Webster and Lukas, 1992, and references therein]. This region, usually referred to as the warm pool, is characterized by some of the warmest water in the World ocean, with sea surface temperature (SST) warmer than 28–29°C over a large area, and relatively low sea surface salinity (SSS < 35) corresponding to a net freshwater flux (precipitation minus evaporation, P-E) of about 1.5 m year⁻¹ [Donguy, 1987]. Because of the high mean SSTs in this region, model results indicate that small (0.5 to 1°C) SST anomalies result in significant changes in the ocean-atmosphere coupling of relevance to ENSO and extra-tropical weather anomalies [Palmer and Mansfield, 1984; Geisler et al., 1985]. Given the importance of salinity and temperature changes in the warm pool, the purpose of the present study is to examine the variability of SSS and SST, taking advantage of in situ data collected via ships of opportunity and moored buoys during 1992–2000.

[3] Based on in situ measurements obtained through ship of opportunity programs, it has been established that the ENSO signal in SSS is predominant in the western half of the equatorial Pacific basin [Delcroix and Hénin, 1991], contrasting with the ENSO signal in SST which is predominant in the eastern half of the basin [Rasmusson and Carpenter, 1982]. During El Niño (La Niña), SSS decreases (increases) in the equatorial band within about 150°E–140°W [Delcroix, 1998], as a result of zonal advection of low (high) salinity water by anomalous eastward (westward) surface
Section 1. Motivations

Additional motivations for studying near-surface salinity in the warm pool include (1) its role in modulating sea level changes [Delcroix et al., 1987; Maes, 1998], and its potential influence on ENSO prediction models assimilating TOPEX/Poseidon sea level data and subsurface temperature data [Li et al., 2000], (2) its role in affecting zonal currents [Acero-Schertzer et al., 1997; Murtugudde and Busalacchi, 1998; Vialard and Delecluse, 1998a; Vialard et al., 2002; Durand et al., 2002], (3) its connection with biogeochemical processes and the carbon cycle [Stoens et al., 1999; Inoue et al., 1996; Loukos et al., 2000], and (4) its relationship with tuna fisheries [Lehodey et al., 1997].


Section 2. Data and Processing Procedures

The SSS data originate from different and complementary sources including measurements collected from the ship of opportunity program (SOOP), from Tropical Atmosphere-Ocean (TAO) moorings [McPhaden et al., 1998], and from research vessels. The ongoing SOOP has been operating since the early 1990s from the Institut de Recherche pour le Développement (IRD) Center in Nouméa, New Caledonia. SSS measurements are based on Seabird SBE-21 thermosalinograph (TSG) instruments installed onboard commercial vessels plying lines from New Caledonia to South-East Asia and/or Japan, with about one section per month. The measurements are collected every 15 s and median values over 5 min are stored. The SSS accuracy is of the order of 0.02 after quality control procedures and post calibration of the sensors. Details are given by Hénin and Grelet [1996] and Prunier-Mignot et al. [1999].

TSG data were also collected from French, USA and Japanese research cruises. These include the COARE-POI cruise from December 1992 to February 1993 [Eldin et al., 1994], the FLUPAC cruise during October 1994 [Le Borgne et al., 1995], the Wespalis 1 and 2 cruises during October 1999 and April 2000 [Hénin et al., 2000; Delcroix et al., 2001], and one to two cruises per year since 1995 from vessels servicing TAO and Triangle Trans-Ocean Buoy Network (TRITON) moorings [see Johnson et al., 2000; Kashino et al., 2001]. All cruise-derived TSG data were calibrated with the help of concurrent CTD measurements, so that the accuracy of these SSS data is probably better than 0.02. CTD and occasionally XCTD casts on these cruises also provided vertical profiles of temperature and salinity. Those from 10 Japanese cruises conducted chiefly west of 165°E in the warm pool region during 1995–2000 [Kashino et al., 2001] will be discussed in detail in this study.
Salinity measurements were also made from TAO moorings in the western Pacific using SeaBird SBE-16 model Seacats. A total of 23 TAO mooring sites were instrumented during 1992–2000 (Figure 1). Temperature and conductivity were sampled at intervals that varied from every 5 to 60 min, depending on the mooring sites. Deployments typically were 6 to 12 months in length, and in most cases sensors were calibrated before and after deployment. CTD casts near the moorings were also made for calibration purposes. Data quality analysis of the salinity records indicated biases due to electronic drift, conductivity cell scouring, and biological fouling of the sensors. However, with postprocessing of the data for quality control purposes, errors in the moored salinity time series were generally reduced to about 0.02°C [Freitag et al., 1999].

SST data were collected at the same locations and dates as SOOP and research vessel SSS data. A total of 34 TAO and TRITON mooring sites also provided SST data (Figure 1). The SOOP-derived SSTs were reduced by 0.2°C in order to account for the warming of seawater in the engine room inside the pipes running from the hull intake to the TSG system. This 0.2°C value is based on statistics performed from research ship measurements only [Hénin and Grelet, 1996], as information was not available for commercial vessels. Overall, the accuracy of the corrected shipboard SST data is probably better than 0.05°C. TAO instrumental SST errors are expected to be about 0.01–0.03°C [Freitag et al., 1995].

The spatial distribution of all SSS and SST data in the warm pool is shown in Figure 1, and the longitude-time distribution of SSS data collected within 2°N–2°S is shown in Figure 2 (a denser distribution applies to SST with, in particular, an almost-continuous time series at 147°E). Figure 1a shows mainly the commercial shipping lines, and Figure 2 further reveals time series measurements at some mooring sites (e.g., 156°E, 165°E and 180°E) as well as zonal sections from cruises (e.g., east of 165°E in October 1994). One should note the poorly sampled region west of about 140°E within 0°–5°N (Figure 1a), where our SSS and SST analyses should be viewed with caution.

Each type of data (SOOP, research vessels, and moorings) was quality controlled separately. In addition, SSS/SST time series obtained at mooring sites were compared to the nearest SOOP-derived measurements as a check on the internal consistency of the moored and shipboard data sets. A comparison (Figure 3) for the 2°S, 165°E...
mooring site which has the most complete SSS time series indicates that the two types of measurements compare quite well, especially given the offsets of 6–10° in longitude and ±0.2° in latitude. Based on similar figures, 2% of SSS and SST measurements were rejected on the assumption that they were erroneous. Finally, the irregularly distributed in space and time SSS and SST data were gridded using an objective Laplacian interpolation scheme [Delcroix, 1998], with a grid element size of 1° latitude, 5° longitude and 1 month. Each type of measurement (from SOOP, research vessels, and moorings) was given the same weight in the gridding procedure.

[15] Strictly speaking, what we call SST and SSS data in this study should be referred to as near-surface temperature and salinity. SOOP-derived data are representative of the water between 4 and 10 m depth depending on the ship and its cargo load. Research vessel CTD data are averages within 0–2 m depth. TAO-derived SSS data were collected between 1 and 5 m depths in most cases, while TAO SSTs are from a depth of 1 m. High resolution measurements in the warm pool have revealed possible occurrences of sharp vertical gradients in the near-surface layer, with differences sometimes reaching as much as 1°C in temperature and 0.5 in salinity between the surface and 5 m depth [Soloviev and Lukas, 1997a, 1997b]. However, when they occur, these gradients are very localized in space and time, and so it is unlikely they could bias the present analysis given our averaging and gridding procedures.

[16] Precipitation (P) data were taken from the CMAP (Climate Prediction Center Merged Analysis of Precipitation) product of Xie and Arkin [1997]. The relative error of the P data is about 25%. Evaporative fluxes were computed using daily mean TAO wind, SST, air temperature, and relative humidity data in the COARE V2.5b algorithm [Fairall et al., 1996]. Monthly means were then computed from these daily estimates at each location. Uncertainties in the monthly averages are estimated to be on the order of 0.1–0.2 m year⁻¹.

[17] The wind data come from the European Remote Sensing Satellite (ERS) wind stress product, as detailed by Bentamy et al. [1998]. Correlation coefficient and RMS differences between the weekly averaged ERS and TAO wind in the warm pool are of the order of 0.9 and 0.8 m s⁻¹, respectively [Quilfen et al., 2000]. The original values of monthly P on a 2.5° by 2.5° spatial grid, monthly E at TAO mooring sites, and weekly wind stress on 1° by 1° spatial

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**Figure 2.** Longitude-time distribution of SSS data collected within 2°N–2°S.

**Figure 3.** Comparison between daily SSS obtained from the 2°S, 165°E TAO mooring (full line) and 1-hour averaged SSS obtained from the nearest merchant ship measurements (crosses) within the region 1.8°S–2.2°S and 171°E–175°E.
grid, were objectively analyzed using the same methods as for SSS and SST, and interpolated onto the same grid.

[18] The surface zonal geostrophic current anomalies were derived from TOPEX/Poseidon sea level anomalies, following procedures described by Delcroix et al. [2000]. As shown by these authors, this TOPEX/Poseidon current product proved very reliable in the warm pool area. When compared to 35-day Hanning filtered zonal currents derived during 1992–1998 from the TAO moorings at the equator and 147°E, 156°E, and 165°E, the correlation coefficients were 0.65, 0.86, 0.90 and the RMS differences were 21, 15 and 16 cm s⁻¹, respectively.

[19] The original 1°-latitude by 5°-longitude by 5-days grid in the current field, filtered with a 35-day Hanning filter, was subsampled every month on the same grid as for SST, SSS, P, E, and zonal wind stress (hereafter T). A 1/4, 1/2, 1/4 time filter was finally applied to each time series and for each variable to reduce possible remaining high-frequency variations not of interest here. A mean was computed over the 4 years period 1993–1996, and anomalies referred to below were calculated relative to this mean.

3. Mean Structures and Standard Deviations

[20] The geographical patterns of mean SSS, P-E, zonal current, T and SST are shown in Figure 4, together with the standard deviations in Figure 5, to provide context for our analysis.

[21] The mean SSS ranges within 34.0 and 34.8, with maximum values near the equator and minimum values to the north and south associated with the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ). SSS increases eastward so that eastward currents would bring low-salinity waters from the west to the east, and vice versa. As inferred from Figure 4, the mean SSS zonal gradient (∂S/∂x) reaches a local maximum value of the order of 0.1 per 5°-longitude within 2°S–4°N and 160°–165°E. These mean values are slightly below (~0.2) existing climatologies [Delcroix et al., 1996; Boyer et al., 1998], reflecting the prominence of El Niño versus La Niña conditions during 1992–2000. The standard deviations of SSS are the same order of magnitude as in the 1974–1989 analysis of Delcroix et al. [1996]. It is noteworthy that the maximum standard deviation (>0.4) appears where mean ∂S/∂x is maximum, suggesting frequent zonal displacements of the associated SSS front during the period analyzed.

[22] The mean P-E somewhat mirrors the mean SSS distribution, with high P-E values roughly corresponding to low SSS values in the ITCZ and SPCZ, and low P-E values corresponding to high SSS values in the equatorial band. The mean P-E is slightly greater than climatology [Delcroix et al., 1996], consistent with the unusually low SSS values during this time period. The mean spatial distribution of P-E mainly reflects P variations in the area, as the mean E is almost constant at 1.4 m year⁻¹ in agreement with the results of Cronin and McPhaden [1998] for the period 1991–1994. The standard deviation in P-E, reflecting mostly the standard deviation in P, increases from west to east, reaching a maximum of 1.6 m year⁻¹ near the dateline.

Figure 4. Mean sea surface salinity, precipitation minus evaporation (P-E, in m year⁻¹), zonal surface current (ZC, in cm s⁻¹), zonal wind stress (Tx; in 10⁻¹ Pa), and SST (in degrees Celsius). All means are for the 1992–2000 period, except the zonal current for the 1987–1992 period. [see Reverdin et al., 1994].
The mean surface zonal current analysis captures the southern part of the North Equatorial Current (NEC) north of 8°N, the North Equatorial Counter Current (NECC) within about 2°N–8°N, and part of the South Equatorial Current south of 2°S. The mean current is almost zero in the equatorial band. Likewise, the mean zonal geostrophic current at the surface is almost zero over our 1993–1996 reference period [Meinen and McPhaden, 2001], suggesting that TOPEX/Poseidon-derived current anomalies can be used with confidence to infer the total (mean + anomaly) current near the equator. The standard deviation in current variability is much stronger than the mean in the equatorial band where variability reaches 20–30 cm s\(^{-1}\), indicative of ENSO-related current reversals as will be discussed below.

The mean zonal wind stress is westward over the whole domain, except west of 150°E in the equatorial band. Maximum standard deviation appears poleward of 6–8° latitudes as well as in the equatorial band from the dateline to 170°E. As discussed below, the off-equatorial standard deviation maxima indicate variations on seasonal timescales, whereas the equatorial maximum is an indication of variations on ENSO timescales.

Mean SST in our warm pool study area ranges from 28.8°C to 29.4°C. These values are very close to previous published values [e.g., Reynolds and Smith, 1994; Antonov et al., 1998]. As noted for zonal wind stress, the standard deviation in SST exhibits local maxima (>0.5°C) away from the equatorial band as a result of seasonal variations and a local maximum in the equatorial band east of 160°E as a result of ENSO-related variations.

4. Variability in SSS, Zonal Surface Current, and P-E

Empirical orthogonal function (EOF) [e.g., Emery and Thomson, 1997] analyses were performed on SSS, P-E, zonal surface current, SST and \(\tau_x\) in order to extract the main modes of variability for these variables. The first EOFs and the percent variance explained by each are shown in Figure 6. The spatial patterns of the first EOF in SSS, P-E and zonal surface current exhibit maximum values in the equatorial band, especially east of 150°E, in agreement with the standard deviation plots (Figure 5). Each temporal function agrees well in phasing with the Southern Oscillation Index (SOI), with clear tendencies to be of the same sign during El Niño events (in 1993–1994 and in 1997) and of opposite sign during La Niña events (from mid-1995 to early 1997 and in 1998–2000). During El Niño, these features indicate the occurrence of below-average SSS, an increase in P-E (primarily due to P), and eastward current anomalies. Opposite tendencies are observed during La Niña events. Computation of lagged correlation coefficients between these EOF time functions indicates that P-E and zonal current time functions precede the SSS time function by 2–3 months, consistent with the fact that it is the time derivative of SSS (\(\partial S/\partial t\)) which is related to P-E and zonal salt advection.

To gain more insight into the signals captured by the EOF analysis, Figure 7 focuses on temporal variability in the 2°N–2°S equatorial band. As expected from Figure 6, the 2°N–2°S averaged SSS anomalies are generally negative during El Niño events (except west of 160°E in 1997–
1998, as discussed below) and as low as −0.8. During La Niña events, SSS anomalies are generally positive, and as high as +0.6. These anomalies are the same order of magnitude as those measured during the 1972–1994 period [Delcroix and Hénin, 1991; Delcroix, 1998]. Time lag correlation analysis indicates that zonal current and P-E anomalies precede SSS anomalies by 2–3 months, as noted above from the EOF analyses. These features are consistent with previous studies that do not include the period 1997–2000 [Picaut et al., 1996; Cronin and McPhaden, 1998; Delcroix and Picaut, 1998; Hénin et al., 1998], indicating that zonal salt advection by anomalous currents together with changes in P play a key role in changing SSS on ENSO timescales in the warm pool.

[28] While the observed 1992–2000 SSS changes were found to be consistent with zonal current and P-E changes,
we recognize that a quantitative analysis should be performed for drawing firm conclusions about the relative contributions of competing processes in the SSS balance. This cannot be done unambiguously with our observations primarily because terms such as vertical advection, vertical mixing, and mixed-layer depth cannot be reliably estimated on the time and space scales of interest with available data. As an illustration of the uncertainty in using a constant mixed-layer depth in the salt conservation equation, as done in some studies [e.g. Delcroix and Hénin, 1991] in the absence of sufficient subsurface data as is the case here, Figure 8 shows two zonal salinity sections obtained from research cruises in September/October 1994 during an El Niño period, and in October 1999 during a La Niña period. In September/October 1994, the depth of the mixed layer (in large part controlled by vertical salinity gradients) averages around 40 m, while in October 1999 it almost doubles and averages around 70 m between 165°E to the dateline. Nonetheless, a quantitative analysis based on the outputs of a forced OGCM simulation, validated with the present SSS data, corroborates the dominant role of zonal advection in changing SSS, with P-E being of secondary importance for the 1992–1999 period [Vialard et al., 2002]. This simulation furthermore suggests that the energetic eastward currents east of about 160°E in the second half of 1997 may result from an enhanced response to the wind-forcing because the BL was thick and the density mixed layer thin at that time.

5. Relationship Between SST, SSS, and Vertical Thermohaline Structure

[29] Ocean-atmosphere coupling during ENSO is important in the warm pool where anomalies in deep atmospheric convection are intimately related to the position of the warmest surface waters. This section thus examines the relation between variations in SST, SSS, vertical thermohaline structure and BL thickness, and how these change in relation to other oceanic and atmospheric variables.

[30] The EOF spatial pattern for SST (Figure 6) is different from the spatial patterns for SSS, P-E, and zonal surface current: negative SST values are found in the equatorial band east of about 155°E but positive values appear elsewhere, with a tendency for off-equatorial extrema in the west. The time function indicates warmer than average surface waters near the equator east of 155°E during El Niño, accompanied by colder-than-average surface waters in the west. These observed SST features are consistent with results obtained for different time periods [Rasmussen and Carpenter, 1982; Wang et al., 1999]. Both seasonal and ENSO-related variability is apparent in the EOF time function for \( t_x \). Only the ENSO-related signal appears when restricting the EOF analysis to the 4°N–4°S band (not shown here), indicating a clear tendency for westerly wind anomalies during El Niño periods and enhanced trade winds during La Niña periods.

[31] Figure 9 presents the 1992–2000 \( \tau_x \) and SST anomalies averaged within 2°N–2°S. These anomalies are in good agreement with those derived from TAO moorings only presented by McPhaden [1999] for the overlapping 1996–1998 period. Figure 9 exhibits an overall tendency for westerly (easterly) wind anomalies during El Niño (La Niña) periods; details about these anomalies and the associated surface zonal current anomalies are given by Delcroix et al. [2000]. In agreement with the EOF analysis, there are apparently two different regimes for the SST anomalies depending on whether or not one is east or west of about 160°E (the mean position of maximum \( \partial S / \partial x \)). West of
160°E, cold SST anomalies occurred mainly during El Niño and warm SST anomalies during La Niña. The reverse situation applied east of 160°E except from mid-1997 to mid-1998 when cold SST anomalies were found at all longitudes west of the dateline, and warm anomalies were located further to the east [Delcroix et al., 2000]. In a Gill-type atmospheric model [Gill, 1980], the associated anomalous zonal SST gradient would result in a positive feedback for El Niño (La Niña) to grow as it would favor westerly (easterly) wind anomalies.

Maximum SST anomalies in the warm pool were of the order of only 1°C, which is about three to five times weaker than the maximum anomalies in the eastern equatorial Pacific. However, these anomalies were superimposed on high mean temperatures so that the absolute SST oscillated around the 28–29°C SST threshold required for deep organized atmospheric convection. As shown in Figure 10, the warmest 2°N–2°S averaged SST (above 29.5°C) occurred when the SOI was close to or above zero, when the eastern edge of the warm pool penetrated into the study region. Remarkably, the warmest SSTs always appeared west of the eastern edge of the fresh pool defined by the 34.75 and 35 isohalines which are markers for the zonal SSS front (Figure 10). Meanwhile, the warmest waters were absent west of 160°E during periods when there was no SSS front to the east.

To statistically illustrate the relationship between the zonal SSS front and SST, we compared 2°N–2°S averaged SST and ∂S/∂x anomalies over 1992–2000. The surface salinity derivative ∂S/∂x, was estimated using centered finite differences over 10 degrees of longitude. A scatterplot of ∂S/∂x and SST anomalies (Figure 11) indicates a significant relationship between these two variables, with an overall tendency for concurrent positive or negative anomalies. Consistent with the idea that the warmest SSTs are linked to thick BLs which form west of the zonal salinity front [Vialard and Delecluse, 1998b; Vialard et al., 2002], the best correlation (R = 0.54) is obtained when SST anomalies are compared to ∂S/∂x anomalies located 5 degrees longitude to the east. The scatter around ∂S/∂x and SST regression indicates that changes in SST are not only affected by BL thickness variations but other mechanisms as well (e.g., changes in net surface heat flux), and that changes in BL thickness could be related to processes other than subduction (e.g., local P-E).

To further document the relation between SST and ∂S/∂x, and because our gridding procedure of the original data as well as the computation of ∂S/∂x over 10° longitude

![Figure 8. Zonal section of salinity in September/October 1994 during El Niño, and October 1999 during La Niña. Contour interval is 0.1. Shaded regions represent salinity less than 34.5. The black circles at station positions denote the depth of the mixed layer, defined by the depth where the vertical density gradient exceeds 0.01 kg m⁻¹.](image-url)
smooths out sharp gradients, we examine a high resolution (1-minute in longitude) equatorial TSG section collected from the Japanese R/V Mirai across 145°E to 170°W during 27 November to 8 December 1999 (Figure 12). At that time, the warmest SST clearly appeared west of the 35 isohaline marking zonal SSS front at the eastern edge of the warm pool. Similar SSS and SST structures were observed from cruise data along the equator in October 1994 [Hénin and Grelet, 1996].

One explanation for the warmest SST in the warm pool involves the coexistence of a thick BL located west of the zonal salinity front [Vialard and Delecluse, 1998b; Vialard et al., 2002]. The availability of 10 zonal CTD sections collected during 1995–2000 allows us to address this question more systematically. Based on the analysis of Lukas and Lindstrom [1991] for the warm pool region, we choose similar gradient criteria to define mixed layer depths from these CTD-derived temperature, salinity and density ($\sigma_\theta$) profiles. The gradients used are $0.05°C m^{-1}$ for temperature mixed layer depth ($dT$), 0.01 practical salinity units (psu) m$^{-1}$ for salinity mixed layer depth ($dS$), and 0.01 kg m$^{-4}$ for density mixed layer depth ($dD$). As given by Lukas and Lindstrom, profiles were scanned downward beginning at 25 m depth until the gradient criteria were exceeded for adjacent 1-m measurements; $dD$, $dT$ and $dS$ were then assigned to the average of the two measurement depths. The barrier layer thickness was defined as the difference between the top of the thermocline minus the depth of the density mixed layer. Longitude-depth sections from two cruises, one with and one without a BL, are presented in Figure 13 to illustrate the application of the gradient criteria. During 19–23 August 1997 (Figure 13), the temperature, salinity, and density criteria resulted in nearly identical mixed layer depths ($dT = dS = dD$). In contrast, during 12–18 November 1999 (Figure 13), there was a shallow halocline embedded in an isothermal layer ($dS < dT$) indicating that the depth of the density mixed layer was controlled mainly by the salt stratification ($dD = dS$).

Using the above criteria, the depth of the temperature, salinity and density mixed layers are presented in Figure 14 for all cruise sections, noting that differences between $dD$ and $dT$ (i.e., the differences between the dashed and solid lines on the longitude-depth plots) are a measure of BL thickness. A BL was always present beneath warm surface water for cruises conducted when a surface salinity gradient was present west of the date line. In contrast, no BL was present when the SSS distribution was quasi uniform from 140°E to the dateline. These relationships are further illustrated in Figure 10, where the 138°E–145°E averaged BL thickness computed for each cruise is shown between the two longitude-time plots for SST and SSS. The average BL thickness ranged between 20 and 30 m during La Niña when SSTs were high in the far western Pacific and was near-zero during El Niño when SSTs were lower in the region. Ando and McPhaden [1997] found similar contrasts in BL thickness.

6. Conclusion and Discussion

In the foregoing sections, we have presented a description of SSS and SST variability in the western Pacific warm pool for the period 1992–2000. The analysis takes advantage of two unique data sets, one from the ship of opportunity program and another from the TAO-TRITON array of moored buoys. This analysis has allowed us to update recent studies of SSS and SST variability in the region through the most recent time period associated with the record breaking 1997–1998 El Niño and the subsequent strong 1998–2000 La Niña.

In conjunction with the SSS and SST analysis, we have also incorporated information from various sources on surface wind stress, surface geostrophic zonal currents, evaporation (E), precipitation (P), and barrier layer thickness. These fields all go through large year-to-year oscillations as a consequence of climate swings related to the ENSO cycle, particularly during 1997–2000. The relationships of these fields to one another, some of which were evident in previous studies of earlier ENSO timescale variations west of the date line [e.g., Delcroix and Picaud, 1998], are apparent in our analysis as well. However, these variations are even more pronounced and better defined in our analysis because of the magnitude of the ENSO warm and cold phase fluctuations during 1997–2000 and, in the case of SSS and SST, because of the availability of data from both ship and buoy platforms. In particular, east of 160°E longitude during the 1997–1998 El Niño, P-E increased (mainly due to changes in P) as the ascending branch of the Walker circulation migrated eastward, and as the ITCZ and SPCZ migrated equatorward. These changes were accompanied by anomalous surface westerly wind stresses, energetic eastward zonal surface currents along the equator, and a sharp decrease in SSS. Opposite tendencies were evident during the subsequent 1998–2000 La Niña.

Our analysis did not allow for a quantitative evaluation of the processes responsible for SSS changes during 1992–2000 in part because we lack sufficient subsurface information to accurately define mixed layer depth on the time and space scales we are interested in. Nonetheless, our results, which encompass the unusually strong ENSO cycle during 1997–2000, are consistent with previous analyses that assign a prominent role to zonal advection and P-E in changing surface layer salinity in the western Pacific [Picaut et al., 1996; Cronin and McPhaden, 1998; Delcroix and Picaud, 1998; Hénin et al., 1998].

Beyond this basic description, we have shown clear relationships between barrier layer thickness and SST in the

Figure 10. Longitude-time distribution of SST and SSS averaged within 2°N–2°S. Heavy lines show the 29.5°C isotherm, and the 34.75 and 35 isohalines. Shaded regions represent SST > 29°C and SSS < 34.75. The right panel represents the Southern Oscillation Index (SOI). The numbers in between the two longitude-time plots denote the barrier layer thickness (in m) averaged within 138°E–145°E.
region west of 160°E. This is a region where vertical processes are likely to exert a significant influence on year-to-year variations in SST, which typically cools during El Niño warm events and warms during La Niña cold events. We developed a proxy indicator for barrier layer formation by the process of subduction in terms of changes in the zonal gradient of SSS ($\partial S/\partial x$) along the equator. This index has been shown in modeling studies to be related to barrier layer formation via subduction driven by converging zonal currents in the vicinity of the salinity front at the eastern edge of the western Pacific warm pool. Correlation between $\partial S/\partial x$ changes and SST changes few degrees longitude to the west was significantly nonzero, consistent with the idea that increased barrier layer thickness is related to warmer SSTs during periods of westward surface flow associated with La Niña, and vice versa during El Niño.

Our analysis of CTD measurements from oceanographic cruises in the region, which allow for definition of barrier layers in relation to SST and SSS variability, supports these conclusions.

[4] The factors responsible for SST change on interannual timescales in the far western Pacific have been poorly documented in the literature. We have pointed out here that the warmest SSTs west of about 160°E occurred when the zonal current was essentially westward, ruling out zonal advection as the dominant mechanism for SST change. Instead, our results suggest that barrier layer formation is a key process in affecting SST in this region. Modeling studies have suggested that BL formation is mainly driven by subduction which has been shown to be influenced by
equatorial Rossby waves [Shinoda and Lukas, 1995; Via- lard and Delecluse, 1998b]. Following the method of Delcroix et al. [1994], the projection of zonal current anomalies onto first baroclinic Kelvin and first meridional mode (m = 1) Rossby waves (not shown here) reveals a strong link between the occurrence of downwelling Rossby waves and warm SST. Since warm SSTs in the region are linked to thick barrier layers, we expect there to be a relationship between Rossby wave dynamics and barrier layer formation as well. There are two possible mechanisms linking the appearance of a thick BL at a given location and downwelling Rossby waves: (1) a zonal displacement of

Figure 13. Longitude-depth sections in temperature, salinity and density ($\sigma_0$). Heavy lines show the 28 and 29°C isotherms, the 34.5 and 35 isohalines, and the 22 and 23 isopycnals. Shaded regions represent temperature $>$28.5°C, salinity $<$34.5, and density $<$22 kg/m$^3$. The line with crosses denotes the depth of the temperature mixed layer, the black circles denote the depth of the salinity mixed layer, and the dashed line denotes the depth of the density mixed layer (see text for mixed layer criteria). Station locations are indicated by the crosses and circles.
the region of thick BL located slightly west of the eastern edge of the warm pool, resulting from westward current anomalies associated with these waves, and/or (2) a differential deepening of the thermocline and halocline since vertical velocities are larger at the deeper depths of the former. The potential roles of these two mechanisms will be dealt with in a subsequent study with the help of OGCM simulations that adequately reproduce our surface-only observations.

[42] As discussed for Figure 12, high-resolution SST and SSS measurements taken along the equator by the end of 1999 illustrate the link between the location of SST warmer than 29.5°C and the zonal SSS front. Also evident are small-scale SSS and SST changes appearing when SST is above 29.5°C, a feature which was observed as well in October 1994 along the equator [Hénin and Grelet, 1996]. An almost coincident CTD section (Figure 13b) reveals that the salinity-controlled density mixed layer was thin and the BL was thick at that time. Hence, it is tempting to speculate that ocean-atmosphere coupling over the warm pool in the presence of a thin mixed layer and thick BL may lead to these small scale SSS and SST features. If so, this means

Figure 13. (continued)
that the spatial decorrelation scales of SSS in this region (and similar regions climatologically) may be smaller than in regions where SSTs are cooler. These regional differences in spatial scales would have to be considered in satellite sampling strategies [Lagerloef et al., 1995] if one wants to resolve the full range of oceanic SSS variability.

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References

Figure 14. Depth of temperature (full line with crosses), salinity (circles), and density (dashed lines) mixed layer (see text for mixed layer criteria). The difference between temperature and density mixed layer depths is a measure of barrier layer thickness. Units are meters. Note the different x-axes for the 10 cruises.


