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Observed correlation of surface salinity, temperature and barrier layer at the eastern edge of the western Pacific warm pool

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[1] Recent theory suggests that ocean-atmosphere interactions in the western Pacific warm pool are of fundamental importance to interannual variations associated with El Niño and the Southern Oscillation (ENSO). The warm pool encompasses the highest mean sea surface temperatures (SSTs) in the world ocean, intense atmospheric deep convection and heavy rainfall, and the formation of thick salt-stratified barrier layers that help to sustain the high SSTs. This study shows that the eastern edge of the warm pool is characterized by a strong zonal salinity front throughout 2002–2004. The analysis also indicates a tighter empirical relationship than previously observed between the eastern edge of the warm pool, high SSTs, the presence of barrier layers, and the fetch of westerly wind bursts. These results suggest that such a frontal region is a critical in controlling ocean-atmosphere interactions in the western Pacific warm pool and highlight the importance of the upper ocean salinity in climate variability. **Citation:** Maes, C., K. Ando, T. Delcroix, W. S. Kessler, M. J. McPhaden, and D. Roemmich (2006), Observed correlation of surface salinity, temperature and barrier layer at the eastern edge of the western Pacific warm pool, *Geophys. Res. Lett.*, *33*, L06601, doi:10.1029/2005GL024772.

1. Introduction

[2] Sea surface temperature (SST) higher than 28°C associated with atmospheric deep convection and heavy rainfall characterizes the western tropical Pacific and defines the warm pool region. The eastern edge of this region is identified, on average, by the presence of a gradient in sea surface salinity (SSS) on the order of 0.4 over 10–15° in longitude. Several observational and modeling studies pointed out that the variability of that eastern edge and of the associated barrier layer and SST is intrinsically linked to the dynamics of the El Niño/Southern Oscillation (ENSO) events [*Picaut et al.*, 1996; *Ando and McPhaden*, 1997; *Delcroix and McPhaden*, 2002; *Maes et al.*, 2002, 2005]. The observational studies were based on spot oceanographic cruises [*Eldin et al.*, 1997; *Rodier et al.*, 2000], on CTD-derived gridded seasonal fields [*Ando and McPhaden*, 1997], and on reconstructed salinity profiles using moored temperature time series [*Maes et al.*, 2004]. While these studies shed light on a number of important features, they do not allow us to define the continuous evolution of the salinity field and of the associated near-surface layer hydrography.

[3] The ongoing collection of data from the Tropical Atmosphere Ocean and the Triangle Trans Ocean buoy Network moorings (TAO/TRITON), the Voluntary Observing Ship (VOS) thermosalinograph (TSG) program and Argo floats now allows a more comprehensive analysis of salinity variability in relation to other environmental variables. The purpose of this note is to describe that variability along the equatorial Pacific Ocean over the period 2002–2004, with special emphasis on the warm pool. The sources of salinity data are described in section 2 and results are presented in section 3. The final section summarizes the results and their implications for understanding ocean-atmosphere interactions.

2. Data and Methodology

[4] Values of SST and SSS were obtained from TAO/TRITON moorings, VOS-TSG and Argo floats. Temperature and salinity profiles with a vertical resolution of 5 to 10 m were further extracted from the Argo floats. Selected profiles with data gaps greater than 30 m in the upper 150 m were not considered (less than 5% of the total larger than 7000 profiles). A few profiles with density inversions larger than 0.002 kg/m^3 below the mixed layer were further corrected. The spurious density values were replaced with values linearly interpolated from temperature and salinity measured at neighboring vertical levels.

[5] The accuracy of the TSG and TAO/TRITON salinity data is believed to be of the order of 0.02 [*Delcroix and McPhaden*, 2002; *Ando et al.*, 2005]. The accuracy of the Argo data is of the order of 0.01 [*Wong et al.*, 2003]. A comparison between the TAO/TRITON and the Argo data was performed as a test of consistency prior to merging these different data sets. We selected all SST and SSS Argo values collected within ±0.5 deg in latitude, ±4 deg in longitude and ±1 day in time of each TAO/TRITON mooring. These time and space scales were based on the characteristic scales of variability that have been determined by *Kessler et al.* [1996] for SST and *Delcroix et al.* [2005] for SSS. The mean differences are negligible and the RMS differences equal to 0.22 and 0.52°C for surface salinity and temperature, respectively,

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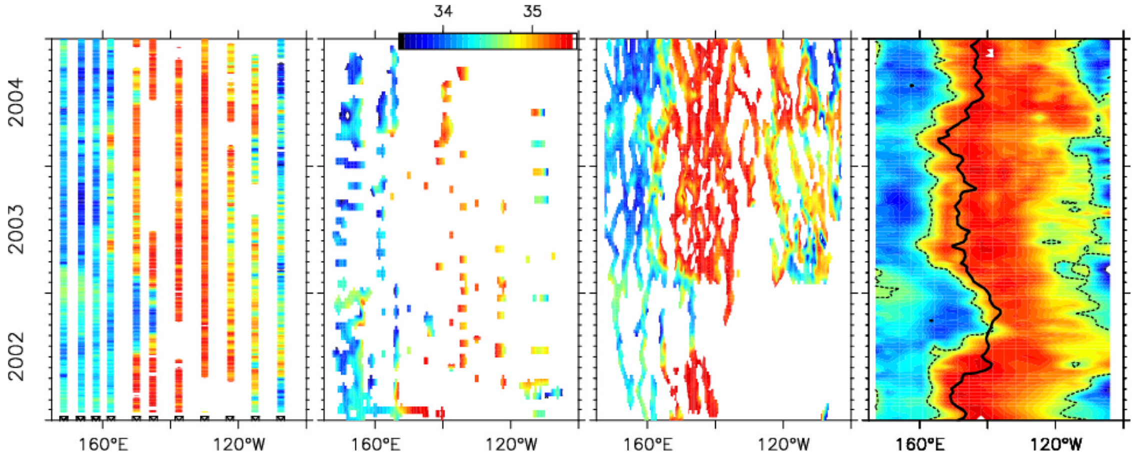

Figure 1. Longitude-time sections for the 3°N–3°S band of sea surface salinity from the TAO/TRITON, the TSG, and the Argo data sets, their combination being represented in the right panel. In the last panel, the thick line represents the 28.5°C isotherm and the dashed line represents the 34.6 isohaline.

which implies a high signal-to-noise ratio in the description of variability that follows.

3. Results

[6] Figure 1 shows the longitude-time plots of the 3°N–3°S averaged SSS. Each individual SSS data set depicts approximately the same general features with, in particular, the suggestion of a sharp salinity gradient near 165°E. Combining the three different sources of SSS using an objective Laplacian interpolation scheme reduces the sampling deficiencies of each data set and yields a coherent picture of large scale SSS. In the central Pacific, SSS values are larger than 35.2 while in the far eastern and in the western Pacific fresh waters with typical values less than 34.2 are found. Moreover, Figure 1 reflects zonal SSS migrations associated with ENSO and, in particular, the eastward displacement of the west Pacific warm pool during the El Niño of 2002–03 [*McPhaden*, 2004]. The most important point revealed by this analysis is the permanent presence of a sharp salinity front, within the 34.6–35.0 salinity range and over 2–3° in longitude, at the eastern edge of the equatorial Pacific warm pool. In comparison, climatological fields exhibit a broad gradient of 0.4 over 10–15° in longitude. Moreover it should be noted that, due to the present sampling of data, the present estimate most likely underestimates the magnitude of the SSS gradient. It is also important to mention that no significant correlation between the zonal displacements of the front and precipitations within the warm pool has been detected.

[7] In contrast to SSS, the SST field does not exhibit a well-marked front along the equator but rather, as expected,

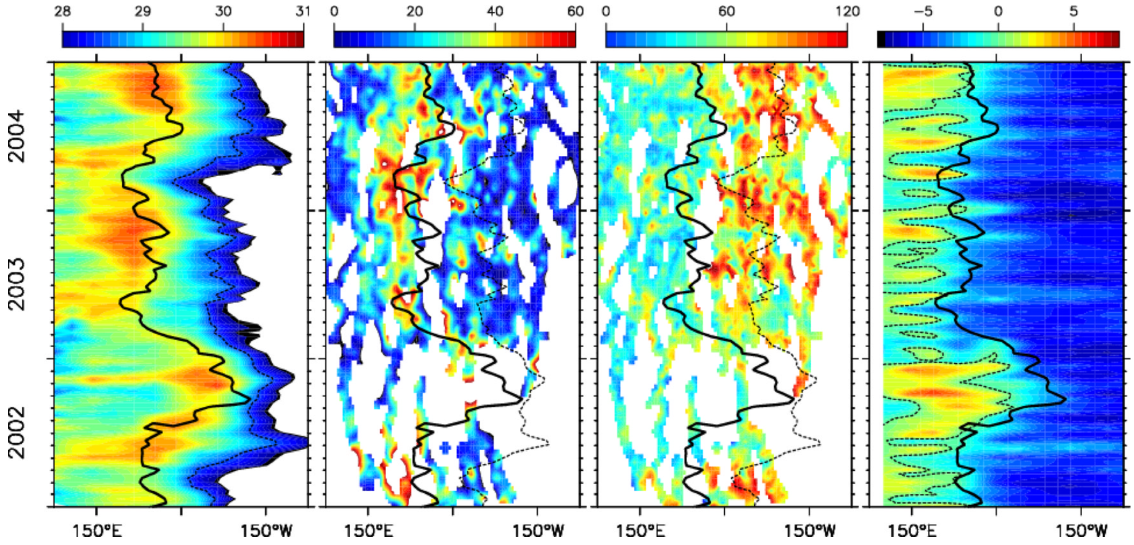

Figure 2. Longitude-time section of SST (°C), barrier layer thickness (m), ocean mixed layer depth (m), and zonal wind (m/s) in the western Pacific for the 3°N–3°S band and during the 2002–2004 period. In all panels the thick black line is the 34.6 isohaline as a mark of the salinity front. In the left panels, the dashed line is the isotherm 28.5°C, whereas in the last panel, it represents the zero line of the wind. The barrier layer thickness is the difference between the isothermal depth and the mixed layer depth. The first one is defined by the depth where the temperature differs from the SST by 0.5°C, while the latter one is determined by a density difference of 0.125 kg/m^3.

a progressive and gradual warming from east to west. This thermal gradient is crucial in driving the surface easterly winds and associated atmospheric convection. In the absence of sufficient salinity sampling, the eastern edge of the warm pool has been often identified by an isotherm ranging between 28° and 29°C. As an example, the 28.5°C isotherm has been superimposed in the combined SSS analysis of Figure 1. Though the seasonal-to-interannual migrations of the salinity front and of the 28.5°C isotherm are usually in phase at timescales longer than about a month, their position along the equator may be separated by up to 20° in longitude. In order to distinguish the two regimes of the central and of the western Pacific Ocean, the present analysis suggests that the salinity front is an important characteristic to consider.

[8] Our finer resolution definition of the frontal zone in salinity at the eastern edge of the warm pool warrants a re-examination of the empirical relationships between the front and the other parameters involved in ocean-atmosphere coupling. Covariability between the salinity front and SST, barrier layer thickness (BLT), ocean mixed layer depth (MLD) and surface zonal wind is shown in Figure 2. The most important result concerns the organization of the zonal gradient of SST. Warmer SSTs are mainly found near and just west of the salinity front with typical values higher than 29.75°C, areas that have been termed SST hot spots [e.g., *Waliser*, 1996]. These areas are also characterized by frequent westerly wind events with maximum values located about 10° longitude west of the front. The permanent presence of such warm SSTs may be associated, on average, with low salinities and with shallow salinity-stratified mixed layers (Figure 1 and Table 1). These mixed layers are moreover insulated from the thermocline by the presence of permanent and relatively thick barrier layers in the order of 30 m (Figure 2 and Table 1). Deep barrier layers can also occur east of the salinity front where SSTs are higher than 28.5°C, but they are more sporadic. Due to the insulating properties of the barrier layer (i.e., reducing or cutting off entrainment cooling at the bottom of the mixed layer and trapping the heat and momentum fluxes in a shallow surface layer), we hypothesize that a positive feedback between barrier layer formation, the fetch of the westerly wind bursts and warm SSTs is operating at the eastern edge of the warm pool. The intensity of the SST-wind coupling that results from the SST hot spots and the WWBs fetch represents an important forcing involved in the generation of downwelling Kelvin waves that propagate eastward.

4. Conclusion

[9] In ocean-atmosphere interactions, the salinity field does not play a direct role as does sea surface temperature. However, the potential exists for salinity variations to feed back indirectly to the atmosphere through their influence on the density stratification of the upper ocean. In the western Pacific warm pool, it has been shown that the trapping of heat and momentum resulting from salinity stratified mixed layers is sufficient to modify the SST balance [*Maes et al.*, 2002, 2005]. The present composite analysis of in situ SSS observations covering the period 2002–2004 period confirms that the eastern edge of the warm pool is characterized by a sharp salinity front of 0.4 over 2–3° in longitude as compared to the broad gradient over 10–15° in longitude as derived from climatology. More importantly, a tighter relationship than previously thought between the salinity front and the warmest SSTs suggests that the intensity of SST-wind coupling is mediated by the presence of salinity barrier layers. Further work including coupled modelling studies will be required to explore these findings in detail.

Table 1. Mean and RMS (in Parentheses) of the BLT and MLD Within the Warm Pool Region (Figure 2)[a]

	BLT	MLD	Total
SST > 29.75°C	30 (19)	44 (18)	590
28° < SST < 29.75°C	18 (18)	62 (28)	1084

[a] The last column indicates the total number of bins per region.

[10] Near the salinity front at the eastern edge of the warm pool, it has been hypothesised that the formation of barrier layer results from the subduction of more saline water from the central Pacific below the less saline water of the western Pacific [*Lukas and Lindstrom*, 1991; *Picaut et al.*, 1996]. While some of the variability of the barrier layer may be explained by this mechanism, the simultaneous presence of a barrier layer, eastward currents (not shown here), and westerly winds also argues for the formation of barrier layer through a tilting/shearing mechanism [*Roemmich et al.*, 1994; *Cronin and McPhaden*, 2002]. Maintenance and expansion of moored and shipboard salinity measurements, further development of the Argo array, and the launch of satellite missions to measure SSS will provide the opportunity to address these questions more rigorously in the next few years.

[11] **Acknowledgments.** The Argo data are collected and made freely available by the International Argo Project and the national programmes that contribute to it (www.argo.ucsd.edu, argo.jcommops.org). The tropical Pacific TSG database is maintained at the IRD centre of Nouméa by David Varillon, as a part of the French “SSS Observations Service” (www.legos.obs-mip.fr/observations/sss/). TAO/TRITON is a joint effort between PMEL and JAMSTEC (these data are freely available at www.pmel.noaa.gov/tao/and www.jamstec.go.jp/jamstec/TRITON).

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