Characteristics of the convergence zone at the eastern edge of the Pacific warm pool

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Received 3 March 2004; accepted 12 May 2004; published 4 June 2004.

[1] The characteristics of the convergence zone at the eastern edge of the equatorial Pacific warm pool are studied using a compilation of in-situ current and salinity measurements during the period 1992–2001. The displacement of the convergence zone is observed, for the first time, as far west as 140°E in the far western Pacific, mainly during La Niña periods, and near 140°W in the central Pacific during the 1997–98 El Niño. The convergence zone may be associated with a salinity front dividing the fresh waters of the warm pool from the salty waters upwelled in the central equatorial Pacific. Despite a zonal displacement ranging over about one fifth of the equatorial circumference of the earth, the characteristics of the main parameters involved in the air-sea interactions are nearly constant on each side of the convergence zone/ salinity front. These results suggest that coupled models used for El Niño research and forecasting should be able to reproduce these important features. *INDEX TERMS:* 4231 Oceanography: General: Equatorial oceanography; 4522 Oceanography: Physical: El Niño; 4572 Oceanography: Physical: Upper ocean processes. **Citation:** Maes, C., J. Picaut, Y. Kuroda, and K. Ando (2004), Characteristics of the convergence zone at the eastern edge of the Pacific warm pool, *Geophys. Res. Lett.*, *31*, L11304, doi:10.1029/2004GL019867.

1. Introduction

[2] If the warming of sea surface temperature (SST) in the eastern Pacific signals the arrival of El Niño conditions, the simultaneous zonal migrations of the western Pacific warm pool and atmospheric convection are also essential precursors of these conditions [*Fu et al.*, 1986]. *Picaut et al.* [1996] demonstrate that the interannual movements of the warm pool are dominated by zonal advection and that they are in phase with the Southern Oscillation (SO). These results lie at the heart of the modification by *Picaut et al.* [1997] of the delayed action oscillator theory in favor of an advective-reflective conceptual model for the El Niño/ Southern Oscillation (ENSO) phenomenon. Hence, the zonal displacement of the warm pool is fundamental for establishing the air-sea interactions in the central-western Pacific that are associated with ENSO.

[3] The importance of the zonal advection was demonstrated by the discovery of a zonal convergence of water masses and of a salinity front at the eastern edge of the warm pool [*Kuroda and McPhaden*, 1993; *Picaut et al.*, 1996; *Delcroix and Picaut*, 1998]. In the central Pacific, the waters are characterized by high salinity (i.e., larger than 35 psu) associated with westward and upward currents. As these waters move westward they are warmed by the net surface heat flux, the SST becomes larger than 28°C and exceeds the threshold for organized atmospheric convection. Near the 29°C isotherm position, a gradient in sea surface salinity (SSS) marks the transition between the waters of the central Pacific and the waters of the warm pool, characterized by salinity typically less than 34.4 psu due to the strong precipitation regime. In the following, the 34.4 isohaline will be used to identify the salinity front and to represent the eastern edge of the warm pool. When the movement of the warm pool is eastward, the zone of convergence also moves eastward and the resulting extension of warm SSTs drives westerly surface winds and sustains atmospheric convection and precipitation. If such conditions persist the development of El Niño has started. On the other hand, during La Niña periods, the movement of the warm pool is westward and the zone of convergence can pass through the eastern edge of the warm pool. However, the displacement of the convergence zone during a complete El Niño-La Niña cycle has not been fully described from in-situ observations, mainly due to the lack of current data in the far western Pacific Ocean.

[4] The average zonal currents in the equatorial waveguide can be used to follow the zonal migration of the warm pool in relation to El Niño [e.g., *Gill*, 1983]. *Picaut et al.* [2001] used hypothetical drifters with huge drogues as a way to highlight the convergence of waters at the eastern edge of the warm pool. In the following, the zone of convergence will be simply defined as the region where the hypothetical drifters converge. One should note that these previous studies using in-situ currents were limited to the central Pacific, i.e., eastward of 156°E, and that during La Niña periods, the trajectory of the hypothetical drifters overreaches this longitude. The linear model used by *Picaut et al.* [2001] suggests however that the convergence zone could be established as far west as 140°E. The availability of additional new current measurements in the far western equatorial Pacific, such as that from the acoustic Doppler current profiler (ADCP) mooring array of the Tropical Ocean Climate Study (TOCS; see *Ueki et al.*, 2003), means that it is now possible to study the displacement of the oceanic zone of convergence in the far western Pacific. In addition, the Triangle Trans Ocean buoy Network (TRITON) moorings that measure SST and SSS will be used to study the relationship between the convergence zone and the salinity front at the eastern edge of the warm pool. These observations are complemented by data from

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0094-8276/04/2004GL019867

Table 1. Comparisons Between Estimated Currents Based on a Mean Vertical Shear and Directly Observed Currents at the 10 m Depth

	Mean (cm s^{-1})	Standard dev. (cm s^{-1})	RMS diff. (cm s^{-1})	Correlation coefficient	Data in common
110°W	10 (−3)	42 (45)	34.0	0.73	670
140°W	−6 (−19)	37 (39)	23.6	0.87	737
170°W	−22 (−24)	28 (28)	9.4	0.94	416
165°E	1.1 (1.7)	37 (36)	13.5	0.93	577
156°E	2.7 (0.4)	39 (35)	12.4	0.95	182

In the first two columns the numbers in brackets are for the estimated currents. Data in common indicates the number of bins averaged over a 5-day period that had both kinds of data present on the same date.

the Tropical Atmosphere-Ocean (TAO) moorings to the east of the TRITON array and by several satellite products at the scale of the equatorial Pacific in order to describe the averaged conditions around the eastern edge of the warm pool during the period 1992–2001.

2. Data and Methodology

[5] Equatorial ADCP currents are available from the TAO/TRITON and the TOCS arrays at 110°W, 140°W, 170°W, 165°E, 156°E, 147°E, 142°E and 138°E. The data extends from depth of 30–50 m to 350 m with typical bin sizes of 10 m. These data are complemented by data from the mechanical and acoustic current meters installed on the TAO/TRITON equatorial moorings. SSS is estimated from the indirect approach developed by *Maes and Behringer* [2000] that uses directly observed SSS when they are available. Daily zonal winds are also provided by the TAO/TRITON array while pentad precipitations are derived from the blended product of *Xie and Arkin* [1997]. All the data sets are interpolated and averaged on a 5-day period corresponding to the current and salinity timeseries.

[6] The ADCP data processing is described by *Johnson et al.* [2000] and by *Ueki et al.* [2003] for the American and Japanese data, respectively. The errors in the processed data are small compared to the large variability that will be described hereafter. The data were typically reduced to 10 m vertical intervals and averaged on a daily basis. Present upward-looking ADCP instruments are unable to make near-surface measurements. Earlier downward-looking instruments did not have this problem. To extrapolate all of the ADCP data to the surface, the vertical mean shear of the top layers was computed from the early ADCP data and from coincident mechanical current meter data. This mean shear was then used to extrapolate the shallowest current value of an ADCP profile (typically at 30 to 60 m) to the surface. Profiles beginning at depths greater than 60 m were discarded. Table 1 gives an idea of the reliability of this approach for the sites at 156°E, 165°E, 170°W, 140°W and 110°W. Westward of 170°W, the RMS differences are less than 15 cm s^{-1} and the differences in mean currents are negligible. The agreement among the different time series is significant (correlation coefficients are larger than 0.9). For the sites eastward of 170°W, there is a mean bias of about 10 cm s^{-1} and the RMS differences increase to values of about 30 cm s^{-1}. In this region, the vertical shear is known to be large and confined to the upper layers. The present use of a mean shear at 30 m would appear to be questionable for estimating surface currents. In any case, the method works satisfactorily in the western-central Pacific, which is the main region of interest in this study, and so it has been applied to the sites at 147°E, 142°E and 138°E.

[7] The timeseries of the surface zonal currents in the far western Pacific are shown in Figure 1. As expected, the current variability is large and Figure 1 shows that, during La Niña periods, eastward currents in the far western Pacific are as large as 1 m s^{-1}. These currents could have an important impact in pushing back to the central Pacific the convergence zone. For instance, the penetration of strong westward currents is clearly seen at 147°E during 1995, but such currents have already weakened at 142°E and a reversal of current occurs at 138°E at the end of this year. This pattern suggests that the convergence zone could be positioned between these two sites.

[8] To follow the displacement of the convergence zone, a 5-day field of surface zonal currents along the equator is built from an objective analysis of the mooring sites. Following *Picaut and Delcroix* [1995], a conversion factor is used to extrapolate the equatorial currents to the 2°N–2°S band. This conversion factor is computed from the ship-board ADCP sections that were routinely occupied between 8°N and 8°S during the TAO/TRITON cruises [*Johnson et al.*, 2000]. A value of 0.7 is found for the sites westward of 170°W, in agreement with the value reported by *Picaut and*

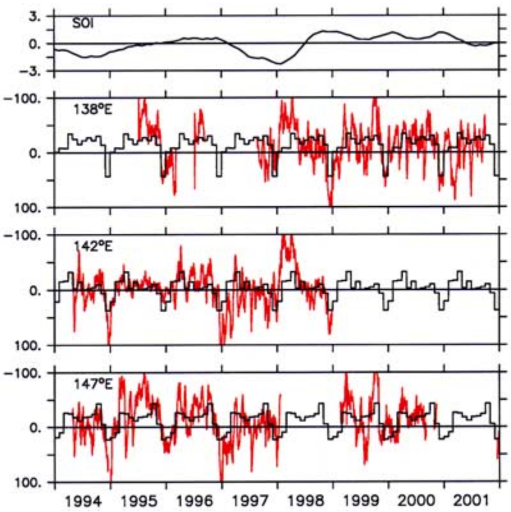

Figure 1. Timeseries of the standardized SOI and of the equatorial surface zonal currents for the sites at 138°E, 142°E and 147°E, from top to bottom, respectively. Units are in cm s^{-1} for the currents. The black lines represent the mean seasonal cycle of the currents for the same period of time. Note that the y-axis has been reversed.

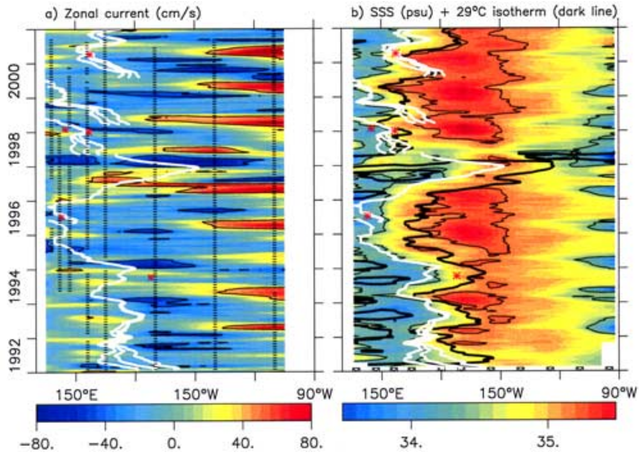

Figure 2. Time/longitude sections of (a) surface zonal currents and of (b) SSS for the 2°N–2°S band during the 1992–2001 period. Units are in cm s^{-1} and psu, respectively. The white lines are the trajectory of the hypothetical drifters and the red stars represent estimations of the eastern edge of the warm pool based on oceanographic cruises (G. Eldin, personal communication). In the left panel, the horizontal tics represent the original sampling of the current data timeseries. In the right panel, the dark line is the 29°C isotherm and squares on the abscissa axis indicate longitudes where TAO/TRITON moorings are positioned.

Delcroix [1995] for the site at 165°E, and a value of 0.9 is found for the sites eastward of this position.

3. Oceanic Zone of Convergence

[9] Figure 2a shows the time/longitude evolution of the zonal surface currents along the equator and the trajectories of several hypothetical drifters with a 2°N–2°S drogue. Only the trajectories useful for studying the relationship between the zone of convergence and the salinity front are considered hereafter. The first series of drifters is "launched" in January 1992 around the dateline and, as expected, they converge into a single trajectory after a period of approximately one year. During a period of 3 years, the drifters remain in the vicinity of the dateline before beginning a westward displacement with the arrival of La Niña conditions in 1995. The quasi permanence of westward currents during this year moves the convergence zone to 138°E by the end of September. At that time, the displacement of the zone of convergence slows between 142°E and 138°E and reverses toward the east by the beginning of December 1995 in association with eastward currents. The duration of these eastward currents is limited to a few months and, finally, the trajectory reaches the western limits of the present current data field. However, due to the lack of observations at 138°E, it is difficult to ascertain if the convergence zone is displaced farther into the western Pacific or if it moves back toward the east. A second series of hypothetical drifters is launched eastward of 147°E and they converge by the end of 1996 between 142°E and 138°E before being displaced toward the central Pacific with the arrival of El Niño conditions of 1997.

[10] The situation is different during the 1998–1999 La Niña and during the period 1999–2000. By the end of 1996, eastward currents prevail from the western Pacific to the central and eastern Pacific in association with the ongoing El Niño conditions. As a consequence, the zone of convergence is strongly displaced eastward until late 1997 when it moves back toward the west. Its easternmost position is, at that time, about 140°W before coming back to about 170°E in less than 6 months (Figure 2a). During a period of approximately one year, the zone of convergence was displaced over a distance greater than 70° of longitude or one fifth of the equatorial circumference of the earth. After that period, the trajectory of the drifters does not necessarily represent the eastern edge of the warm pool due to the strong perturbations associated with the 1997–98 El Niño and its abrupt shift toward La Niña. In particular, the salinity front is blurred by the presence of rainfall in the central and eastern Pacific. A third series of drifters is launched in the western Pacific and shows by mid 1999 that the convergence zone is moved toward the limits of the present data set westward of 138°E. Once again, it is difficult to ascertain the real movements of the convergence zone due to the lack of observations at 142°E at that time. The same remarks hold for the period that follows with the exception that convergence zone could not persist in the vicinity of the dateline because of the divergent currents in this region (Figure 2a). A final series of drifters is launched near the dateline by the end of 2000 and the trajectory converges in the western Pacific near 160°E before exhibiting an eastward displacement caused by the ongoing conditions of the 2001 El Niño.

4. Relationship With the Salinity Front

[11] Directly observed and reconstructed SSS at the TAO/TRITON sites are used to investigate the relationship between the convergence zone and the eastern edge of the warm pool. Figure 2b displays the time/longitude evolution of the SSS for the 2°N–2°S band, the position of the 29°C isotherm and the trajectories of the hypothetical drifters as previously discussed. Most of the time, the zonal displacements of the different parameters used to represent the eastern edge of the warm pool are well correlated with each other. The main exceptions to this rule happen at the end of 1997 and during La Niña periods of 1995–96 and 1998–99. For the first period, the strong eastward currents associated with the 1997 El Niño event moves the convergence zone farther into the central Pacific than the salinity front. For the last two periods, the freshwater input from the atmosphere into the far western Pacific overrides the effect of the zonal advection and consequently, the salinity front appears to be not correlated with the convergence zone. Finally, one should note that the present estimates of the position of convergence zone/salinity front agree relatively well with the few direct observations (Figure 2).

[12] During the period 1992–2001, the zonal displacement of the salinity front associated with the eastern edge of the warm pool is located between 138°E and 170°W. The 34.4 psu isohaline is used to represent the position of the salinity front and the other parameters are averaged around this position to summarize the averaged conditions localized at the eastern edge of the warm pool. Figure 3 displays the time-averaged fields of SST, surface zonal current, surface zonal winds and precipitation at locations within 25° of longitude on each side of the central position of the salinity

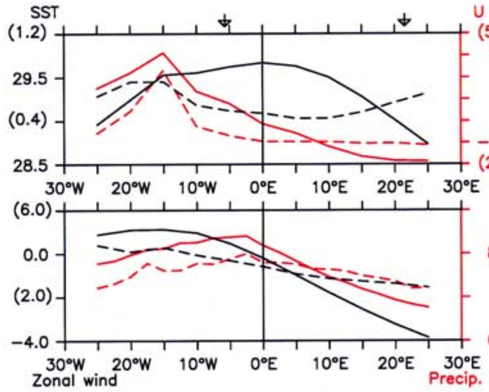

Figure 3. Time-averages (solid lines) and standard deviations (dashed lines) of (top) SST (black) and surface zonal currents (red), and of (bottom) surface zonal winds (black) and precipitation (red) for locations within 25 degrees east and west of the salinity front as defined by the 34.4 psu isohaline. Units are in °C, cm s^{-1}, m s^{-1}, and mm/day, respectively. The horizontal axis indicates the location in degrees relative to the position of the moving salinity front. The vertical axes have scales for each of the parameters with brackets indicating values for the standard deviation when its scale differs from that for the time-average. On the top of the figure, the left arrow indicates the position of the SSS minimum while the right arrow indicates the eastward position where SSS becomes larger than 35 psu.

front where SSS equals 34.4 psu. SSS values larger than 35 psu are found 20° of longitude eastward while the minimum SSS values, around 34.2 psu, are found 5–10° of longitude westward. These features are in agreement with the schematic picture of the warm fresh pool proposed by *Hénin et al.* [1998]. On each side of the front, the SST remains larger than 29°C with a maximum value of 29.5°C near the front and a variability less than 0.5°C. Eastward currents as large as 10 cm s^{-1} are found westward of the front at a distance of 15° of longitude. The position of the eastward currents also corresponds to the position of the maximum variability (around 40 cm s^{-1}). Surface zonal westerly winds are associated with the eastward currents while easterly winds blow on the eastward side of the front. The zero crossing of the winds is coincident with the central position of the front. The maximum value of precipitation is found in the westward side of the front while a large gradient characterizes the eastward side, in agreement with the salinity characteristics. The most important point to notice is the near constant magnitude of the variability of all the aforementioned parameters over 10° of longitude on each side of the central position of the salinity front (Figure 3).

5. Conclusion

[13] The zone of convergence on the eastern edge of the warm pool associated with a well-defined salinity front separates the warm pool of the western Pacific from the cold tongue of the eastern Pacific. The zonal displacements of the warm/fresh pool along the equatorial band represent an intrinsic element of the ENSO system. Based on directly observed currents the present study finds the convergence zone during La Niña periods as far west as 140°E in the western equatorial Pacific. In this region, the otherwise dominant contribution of the zonal advection could be surpassed by local precipitation in the surface salinity budget, leading to an apparent decorrelation between the convergence zone and the salinity front. Despite a displacement of several thousands of kilometers, the main characteristics at the eastern edge of the warm pool are remarkably constant over a distance of 1000 km on each side of the salinity front. This suggests that it is important to simulate similar characteristics of the Pacific Ocean in coupled models used for ENSO research and forecasting.

[14] **Acknowledgments.** The authors would like to thank the TAO project and its director Michael McPhaden, Gregory Johnson, Dave Behringer, Jacqueline Boutin, Gérard Eldin, Lionel Gourdeau and Thierry Delcroix. TRITON and TOCS projects are supported by the Ministry of Education, Culture, Sports, Science and Technology in Japan. The first two authors are supported by the Institut de Recherche pour le Développement (IRD) in France.

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