Upper and intermediate circulation in the western equatorial Pacific Ocean in October 1999 and April 2000

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[1] The upper and intermediate circulation (0–1200 m) in the western equatorial Pacific Ocean is examined thanks to Lowered Acoustic Doppler Current Profiler (LADCP) measurements carried out during two cruises in October 1999 and April 2000. Several new features of the equatorial circulation are discussed. It is shown that the secondary South Subsurface CounterCurrent (sSSCC) laying at 6°S–400 m depth, had a deep extension at 165°E with a maximum core velocity around 5°S–1000 m. Furthermore the Equatorial Intermediate Current (EIC) and the Lower EIC (LEIC) displayed a strong temporal variability between 165°E and 180°, as these two westward currents were replaced by eastward flow along the equator on the second cruise. Finally during the April 2000 cruise the zonal velocity profile carried out at the equator east of the Gilbert Island (around 175°E) broke into small vertical scales, possibly reflecting topographic effect and/or destabilization mechanism that leads to the formation of long zonal jet-like structures. **Citation:** Gouriou, Y., T. Delcroix, and G. Eldin (2006), Upper and intermediate circulation in the western equatorial Pacific Ocean in October 1999 and April 2000, *Geophys. Res. Lett.*, *33*, L10603, doi:10.1029/2006GL025941.

1. Introduction

[2] Since the 1980's, the generalization of Acoustic Doppler Current Profiler (ADCP) measurements has considerably increased our knowledge of the three-dimensional circulation of the upper layers in the equatorial Pacific Ocean [see *Rowe et al.*, 2000; *Johnson et al.*, 2002]. Papers dealing with direct current measurements below 500 m are less numerous, but two of them have provided some clues on the intermediate and deep circulation across the Pacific Ocean. In the first paper, *Firing* [1987] discussed 41 velocity sections made at 159°W, between 3°N and 3°S, in 1982–1983. The mean meridional section revealed persistent intermediate and deep currents. In the second one, *Firing et al.* [1998] gave some indices on the zonal scales of these currents by analyzing 10 non-synoptic meridional velocity sections taken across the equatorial basin between 146°E and 86°W.

[3] Poleward of 4° latitude, *Rowe et al.* [2000] reported the presence of a subthermocline current, below 300 m, 1°–2° south of the South Subsurface Counter Current (SSCC). They called it the secondary SSCC (sSSCC), and indicated that this current was generally observed between 180° and 120°W and sporadically outside that longitude band. However they showed a section at 165°E where this current was clearly apparent at 6°30′S with an eastward velocity maximum at 400 m, maximum depth of the measurements. To our knowledge, there is no reported observation of the complete vertical extension of that flow.

[4] Based on *Firing* [1987], *Rowe et al.* [2000], and observations discussed in this paper, Figure 1 displays a schematic of the zonal circulation from the surface to 1200 m depth. Not visible here, smaller vertical-scale currents are superimposed on the equatorial currents between 1°N and 1°S from below the thermocline down to 2500 m, known as Equatorial Deep Jets (EDJ) [*Eriksen*, 1981; *Leetmaa and Spain*, 1981; *Firing*, 1987]. *Firing et al.* [1998] showed that zonal currents below 400 m are most likely basin-wide features.

[5] Very few driving mechanisms of the above-mentioned subthermocline currents are presently being proposed, as observations are still too sparse. Any new observation is thus potentially valuable to expand our knowledge. Hence, as a contribution to the field, this note presents sections of 0–1200 m direct velocity measurements carried out in the western Pacific in October 1999 and April 2000, both along 165°E and 180° (0°–10°S) and along the equator from 165°E–180° (Figure 2). During these cruises, measurements were made in the vicinity of the Gilbert Islands (Kiribati), which straddle the equator, where *Eriksen* [1981] led an experiment in 1978 to explore the existence of EDJ and the possible impact of the islands chain on the oceanic circulation.

2. Data

[6] Data discussed in this paper were acquired during the Wespalis 1 (October 14 to November 9, 1999) and Wespalis 2 (April 13 to May 12, 2000) cruises during which we conducted 0–1000 m Conductivity-Temperature-Depth (CTD) measurements with a Sea-Bird 911+ probe as well as 0–1200 m velocity measurements with a RD Instrument 150-kHz Lowered Acoustic Doppler Current Profiler (LADCP) attached to the rosette (see stations locations on Figure 2). LADCP measurements were processed following the method described by *Fischer and Visbeck* [1993]. Detailed information about the cruises, CTD calibration and LADCP processing can be found in the cruise reports [*Hénin et al.*, 2000; *Delcroix et al.*, 2001].

3. Observed Circulation

3.1. Zonal Circulation at 165°E (Figure 3)

[7] The two sections present a noteworthy variability between October 1999 and April 2000, especially below

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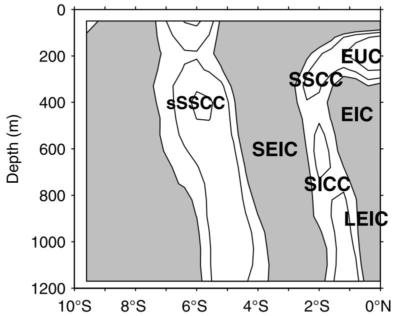

Figure 1. Schematic of the zonal tropical circulation south of the equator. Shaded areas show regions of westward flow. EUC, Equatorial Undercurrent; SSCC, Southern Subsurface Countercurrent; sSSCC, secondary SSCC; EIC, Equatorial Intermediate Current; LEIC, Lower EIC, SEIC, South Equatorial Intermediate Current; SICC, South Intermediate Countercurrent.

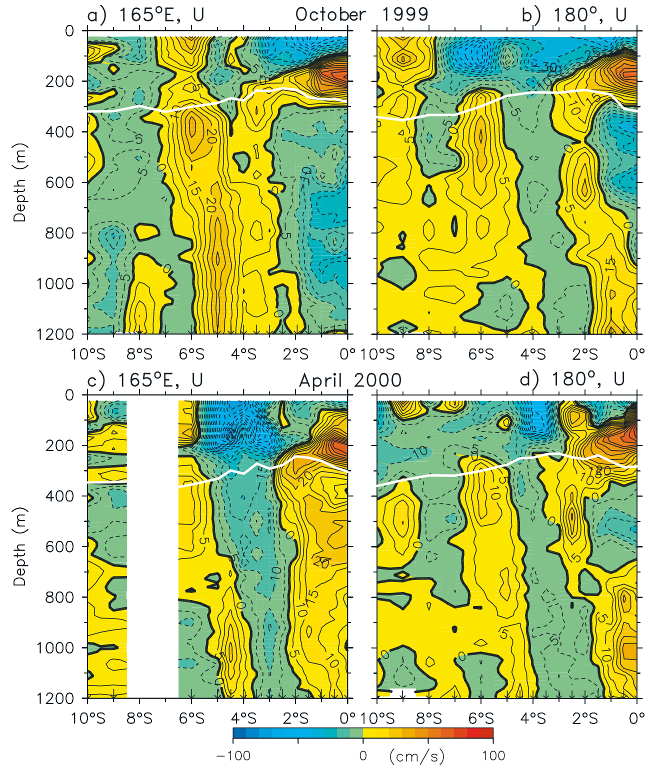

Figure 3. Latitude-depth sections of the zonal component of the velocity, in cm s^{-1}, at (a) 165°E in October 1999, (b) 180° in October 1999, (c) 165°E in April 2000, and (d) 180°E in April 2000. Potential isopycnal 26.5 kg m^{-3}, denoting the base of the thermocline, is superimposed on the plots (white line). Station positions are shown at the bottom of every plot.

300 m. Within about 0°–2°S, the current was westward in October 1999 and eastward in April 2000. The April 2000 section looks like a December 1989 section at 155°W and a June 1983 section at 159°W shown by *Firing et al.* [1998].

[8] *Firing et al.* [1998] noticed that when the EIC/LEIC westward flow was replaced by an eastward flow, the SICC could not be easily identified, as it was the case in April 2000. On the other hand when the EIC/LEIC is present, the SICC and NICC are clearly visible. From the available set of sections, *Firing et al.* [1998] drew the conclusion that the SICC and NICC were the most robust currents at intermediate depths across the Pacific Ocean. Our October 1999 section did not show up any SICC, implying that it is also subject to some kind of variability.

[9] The westward flowing SEIC is difficult to detect in October 1999, as only a minimum of eastward velocity and some patches of weak westward currents are visible along a slanted line from 5°S–200 m to 2°30′S–1200 m. In contrast, the SEIC is present in April 2000 ranging from 4°S–400 m to 3°S–1200 m.

[10] South of 4°S, both sections at 165°E reveal a column of eastward current extending from about 6°S–300 m to 5°S–1200 m, with two cores of maximum eastward velocity at 6°S–400 m and 5°S–1000 m. The shallowest velocity core centered on 400 m at 6°S is the sSSCC described by *Rowe et al.* [2000]. They reported that the sSSCC appears intermittently west of the dateline. As the sSSCC deepens from east to west, to reach about 300 m at 160°E, there is a possibility that the small number of observations west of 180° is due to an insufficient sampling range of 150 kHz ship-mounted ADCPs, whose profiles barely reach 250 m during the Wespalis cruises. Our observations do evidence that the sSSCC was present at 165°E in October 1999 and April 2000 (as well as at 180°, see below). The lower eastward velocity core at 1000 m–5°S has never been mentioned in the literature.

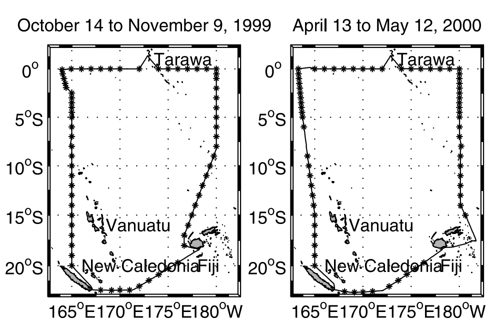

Figure 2. Tracks of the Wespalis1 and Wespalis2 cruises. Positions of LADCP profiles are shown by dots.

3.2. Zonal Circulation at 180° (Figure 3)

[11] The sections taken in October 1999 and April 2000 present very similar current patterns within 0°–7°S, contrasting with the two sections at 165°E. Within about 0°–2°S, the westward flowing EIC and LEIC were present within 300–900 m in October 1999 and within 350–650 m in April 2000. In October 1999, the eastward flowing SICC was composed of two distinct velocity cores at 2°S–600 m and 1°S–1100 m. In April 2000, the upper core was centered on 2°30′S–500 m and the lower core can hardly be differentiated from the eastward flow occurring within 0°–1°30′S. The westward flowing SEIC was present in October 1999 and April 2000 from 4°S–300 m to 2°30′S–1200 m. Within about 4°S–6°S, eastward flows found at 165°E were also present in the 180° sections. In October 1999 the upper core (sSSCC) was centered on 6°S–425 m,

reaching 25 cm s^{-1}, and the sSSCC lower core was apparently not present. In April 2000 the velocity of the upper core at 6°S–400 m was slightly weaker (15 cm s^{-1}) and there is a hint for the lower core to be present within 700–1200 m and 4°S–5°S.

3.3. Zonal and Meridional Circulation Along the Equator (Figures 4 and 5)

[12] As noted above for the 165°E and 180° longitudes, one remarkable feature is the reversal of the zonal circulation below the EUC, with westward current within 300–1200 m in October 1999 (except east of about 175°E within 900–1200 m) and eastward current in April 2000 (except east of about 178°E within 400–600 m). These measurements show that the reversal occurred over at least 15° of longitude.

[13] Also remarkable, in April 2000, are the changes in the vertical shape of the zonal and meridional currents that took place east of the Gilbert Islands (174°E) while steaming from 163°E to 180° (compare Figures 5a–5c). The second zonal velocity profile, at 175°E, taken after the call at Tarawa displayed smaller vertical scales, of the order of 100 m at 500 m depth increasing to 200 m at 1000 m depth, than those generally attributed to EDJs [*Firing*, 1987].

[14] The EUC seemed to be also affected, with the emergence of a secondary maximum in eastward velocity just above that current. This secondary maximum progressively deepened, to reach 150 m, and its velocity increased in the next stations while the main EUC-core velocity decreased to 60 cm s^{-1}. At 178°E the EUC could be viewed as the superimposition of two velocity cores (Figure 5d). Then at 180° the EUC core recovered its 'classical' vertical shape and its velocity increased to 80 cm s^{-1} (not shown). Reversing jets in the upper layers have already been observed in the western equatorial Pacific Ocean [*Hisard et al.*, 1970; *Kuroda and McPhaden*, 1993]. Following westerly wind bursts (WWB) the upper currents displayed a 3-layer structure with an eastward flow at the surface, a westward flow underneath and then the eastward flowing EUC. *Cronin et al.* [2000] demonstrated that the westward flow above the EUC was a consequence of zonal pressure gradients set up by the WWB [see *Kennan and Niiler*, 2003]. However, the TAO-TRITON wind measurements at 165°E and 180°E did not show any WWB during the month preceding the 2000 cruise. Furthermore the surface current was constantly westward during the 2000 cruise. Thus the upper-layer zonal flow at 178°E differs from preceding observations though, as we lack temporal and spatial resolution, we cannot conclude as to whether or not this is related to the small-vertical scales observed below the thermocline or to the mechanisms proposed by *Cronin et al.* [2000].

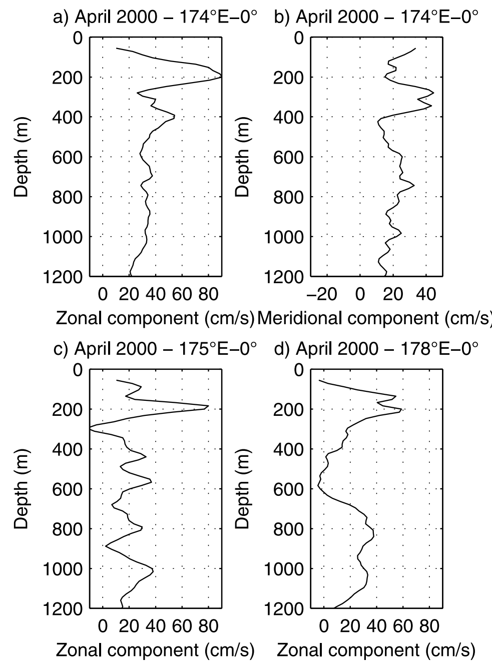

Figure 5. LADCP velocity profiles, in cm s^{-1}, in April 2000 of the (a) zonal component at 0°–174°E, (b) meridional component at 0°–174°E, (c) zonal component at 0°–175°E, and (d) zonal component at 0°–178°E. Westward and southward velocities are negatives.

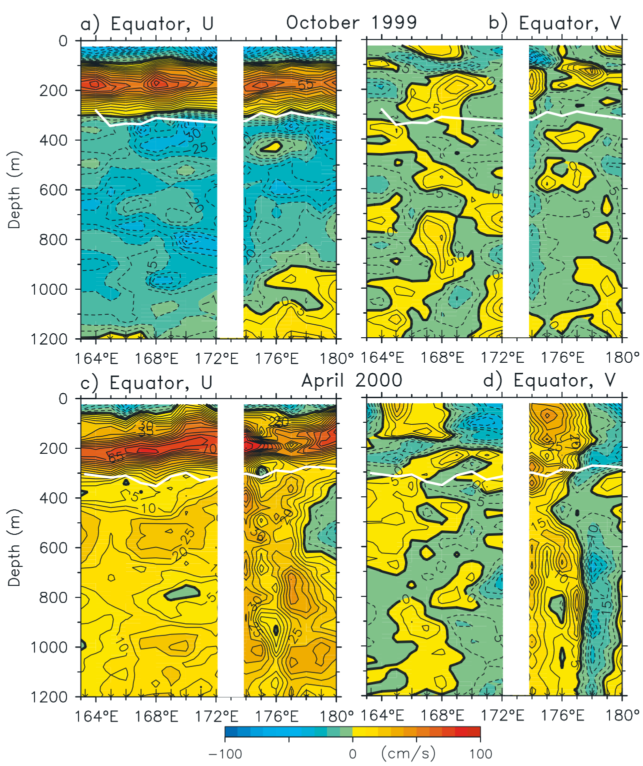

Figure 4. Longitude-depth sections of the LADCP velocity, in cm s^{-1}, along the equator for the (a) zonal component in October 1999, (b) meridional component in October 1999, (c) zonal component in April 2000, and (d) meridional component in April 2000. Potential isopycnal 26.5 kg m^{-3}, denoting the base of the thermocline, is superimposed on the plots (white line). Station positions are shown at the bottom of every plot.

[15] It is noteworthy that the meridional component of the current was also dramatically altered east of the islands chain, the velocity (northward around 20 cm s^{-1}) being nearly barotropic over the available depth range (Figure 5b). *Eriksen* [1981] reported that a velocity profile taken near the Gilbert Islands at 0°20′S–173°55′E had few vertical zero-crossings and showed southwestward flow below the ther-

mocline. He supposed that the tidal flow was enhanced by the island chain. It is worth noting that the barotropic tides were removed from our LADCP velocity data by using the OSU TOPEX/POSEIDON model version TPXO.3 [*Egbert et al.*, 1994] and that at the time of the 2000 cruise the model tidal current did not exceed 1 cm s^{-1} along the equator.

4. Conclusion

[16] The October 1999 and April 2000 current measurements substantiate the overall peculiarity of the upper and intermediate circulation in the western equatorial Pacific Ocean. Although rarely observed west of the dateline before, we identified the secondary sSSCC during both cruises at 165°E and 180° and a deep extension of this eastward flow with a new core around 1000 m depth underneath. *Richards et al.* [2006] have recently discussed the results of two high horizontal resolution ocean models (1/10° at the equator). Alternating jet-like structures with fine meridional scales are clearly seen in both models, most notably between 30°N–55°N and in the tropics. Our observations of alternating horizontal jets give some credit to these model results, except for the high vertical wavenumber of the observed EDJs which shows up in our observations only.

[17] As also reported by *Firing et al.* [1998] we further observed that the equatorial sections showed a high degree of variability in the zonal currents commonly referred to as the EUC, EIC/LEIC, SEIC. In particular, we show that the EIC/LEIC were largely replaced by an eastward flow along the equator on the second cruise. Transport of the EIC/LEIC at 165°E between 2°30′S and the equator and from 350 m to 1200 m thus varied from 28.6 Sv westward in October 1999 to 26.2 Sv eastward in April 2000. If the reverse of the EIC/LEIC was symmetrical about the equator, as shown by *Firing et al.*'s [1998] sections, these transports must be doubled. This huge transport variability cannot be ignored when discussing the zonal mass balance of the equatorial Pacific Ocean. Besides, the previously estimated stable SICC was also subject to strong variability between our two cruises.

[18] Finally, both the zonal and meridional current components changed after the call in Tarawa in April 2000, at times of eastward current, suggesting that the Gilbert Islands topography may play a role in the vertical structure of the circulation (a detailed map of the island topography is given by *Eriksen* [1981]). Surprisingly, such changes did not happen during the first cruise (October 1999) at times of westward currents. B. L. Hua et al. (Destabilization of mixed Rossby gravity waves and equatorial zonal jets formation, submitted to *Journal Fluid Mechanics*, 2006) have studied the effect of destabilization of mixed Rossby gravity waves as a possible formation mechanism for EDJs. In the case of short waves (i.e., with strong zonal shear of meridional velocity, $\partial v/\partial x$), the destabilization mechanism leads to the formation of long zonal jet-like structures, with high vertical wavenumber. Hence, an alternative hypothesis for the current changes past the Gilbert Islands in April 2000 is that we did capture this instability mechanism given the strong $\partial v/\partial x$ observed at that time. This does remain an outstanding issue that needs to be clear up.

[19] It is not possible here to draw conclusions about the permanence of all those currents, or analyze the causes of variability. However, we can say that Tropical Instability Waves [*Chelton et al.*, 2000] have been found to be active in the region in October 1999 and April 2000, and that variable wind forcing is known to be responsible for variations in the currents extending throughout the upper water column and thermocline [*Cronin et al.*, 2000; *Kennan and Niiler*, 2003]. It is hoped that our new observations will stimulate the interest of modelers and theoreticians who are trying to solve the intermediate ocean circulation puzzle.

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