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# Structure of the upper deep current in the Melanesian Basin, western North Pacific

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**Abstract**: We used velocity and echo intensity data obtained from a lowered acoustic Doppler current profiler to clarify the structure of the upper deep current at depths of 2000–3500 m over the northeastern slope of the Solomon Rise in the Melanesian Basin, western North Pacific. This current separates from the Antarctic Circumpolar Current and flows northward, carrying oxygen–rich Upper Circumpolar Water. The current comprised western and eastern cores located over the bottom slope at water depths of approximately 3000 and 4000 m, respectively. Between the double cores of the current, a thick countercurrent was observed with a width of more than 100 km. The countercurrent flowed over the bottom slope at a water depth of approximately 3500 m and carried water that is characterized by extremely high echo intensity. These observations suggest that the equatorial eastward current observed at the southern boundary of the East Caroline Basin is steered by the bottom slope and connects to the countercurrent in the Melanesian Basin, carrying equatorial water with high echo intensity.

***Keywords:*** *LADCP, upper deep current, Upper Circumpolar Water, western North Pacific*

## 1. Introduction

Within the deep layer in the Pacific Ocean at depths of 2000–3500 m, hereafter termed the upper deep layer, oxygen–rich water originating from Upper Circumpolar Water (UCPW) is carried by an anticyclonic gyre in the South Pacific after leaving the Antarctic Circumpolar Current (REID, 1997). The current in the upper deep layer, hereafter termed the upper deep current, flows along the 2500 m isobath in the equatorial South Pacific, passing through the northeastern slope of the Solomon Rise in the Melanesian Basin (KAWABE *et al.*, 2003). The upper deep current in the equatorial region is located on the onshore side of the deep western boundary current in the lower deep layer below 3500 m; the deep western boundary current carries Lower Circumpolar Water (LCPW) from the Antarctic. The upper deep current enters the Philippine Sea, forming several branch currents that flow into the East and West Caroline Basins and the West Mariana Basin. The transportation of UCPW leads to elevated oxygen levels in the Philippine Sea (KAWABE, 1993; KAWABE *et al.*, 2003).

KAWABE *et al.* (2006) used moored current meters at depths of 1880–3750 m at five mooring sites (ML1–ML5) to observe the velocity of the upper deep current within the Melanesian Basin from February 1999 to February 2000. The upper deep current was recorded at depths of approximately 2000–3500 m at ML1–ML3 (3°23′N, 159°30′E to 5°07′N, 160°52′E), with the largest magnitude recorded in the middle of this layer. They also found that the structure of the upper deep current has two states and that it changes sharply between them. In the state observed during the first half of the observation period, a strong countercurrent flows at ML1 and the upper deep current flows at ML2 and ML3. In the other state observed during the second half of the observation period, the upper deep current is especially strong at ML1 and flows at ML1–ML3.

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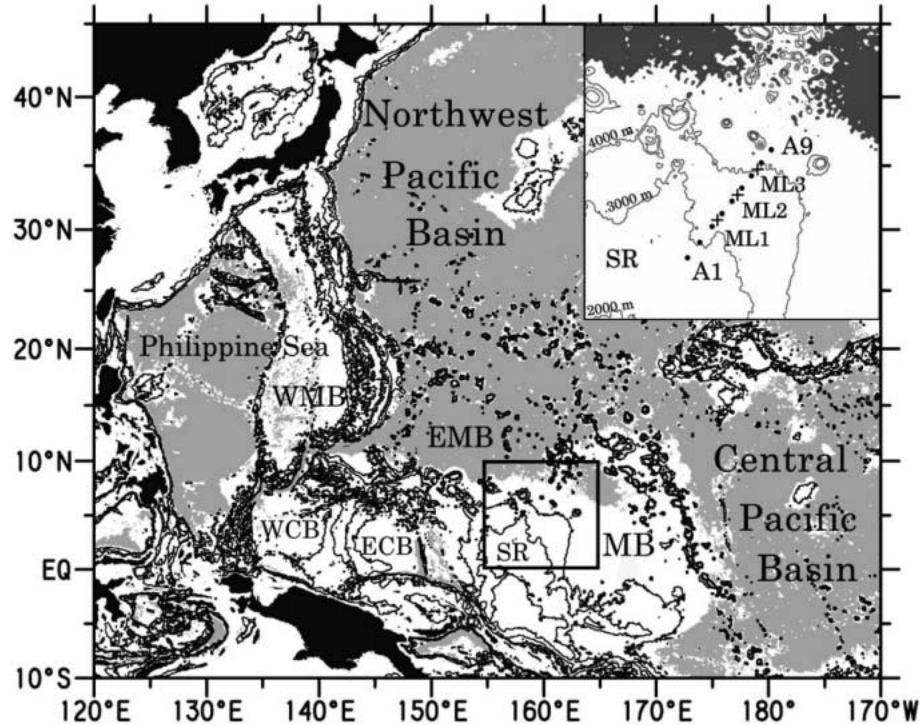


Fig. 1. Map of the western Pacific with an enlarged view (inset map; see the square on the main map for the location of the inset map) of LADCP stations A1–A9 (dots) and moorings ML1–ML3 (crosses) on the slope of the Solomon Rise within the Melanesian Basin. Contours are isobaths at 2000, 3000, and 4000 m. Shading represents areas at depths greater than 5000 m. MB, Melanesian Basin; SR, Solomon Rise; EMB, East Mariana Basin; WMB, West Mariana Basin; ECB, East Caroline Basin; WCB, West Caroline Basin.

On the basis of the distribution of dissolved oxygen and geostrophic velocity, they inferred that the upper deep current during the first half of the observation period extended to the west of ML1 and was divided into western and eastern cores by the countercurrent. This inference may be correct, but should be confirmed by direct measurement of current velocity, since oxygen data do not directly show a current, and geostrophic velocity includes an ambiguity from an assumption of a reference depth. For this purpose, velocity data from a lowered acoustic Doppler current profiler (LADCP) are suitable.

In the present paper, we confirm the double–core structure of the upper deep current in the Melanesian Basin and clarify the lateral extension of the current cores and the countercurrent by analyzing current velocity data obtained using an LADCP. Moreover, we discuss the origin of the countercurrent using data of echo intensity from LADCP, which reflects the amount of particulate scatterers and is expected to indicate the characteristics of water masses.

## 2. Observations and method

We used LADCP data obtained at nine stations, A1–A9, located between 2°05′N, 158°30′E and 5°46′N, 161°20′E within the Melanesian Basin (Fig. 1). The data were collected during the period 30 January-2 February 1999 on the R.V. *Hakuho Maru* KH–99–1 cruise using a 300–kHz LADCP manufactured by RD Instruments (RDI). Current velocity data obtained using the LADCP were processed following the method of Komaki and Kawabe (under review); that is, we fitted the LADCP velocity profile to current velocity at depths of 100–800 m measured using a 38-kHz RDI shipboard

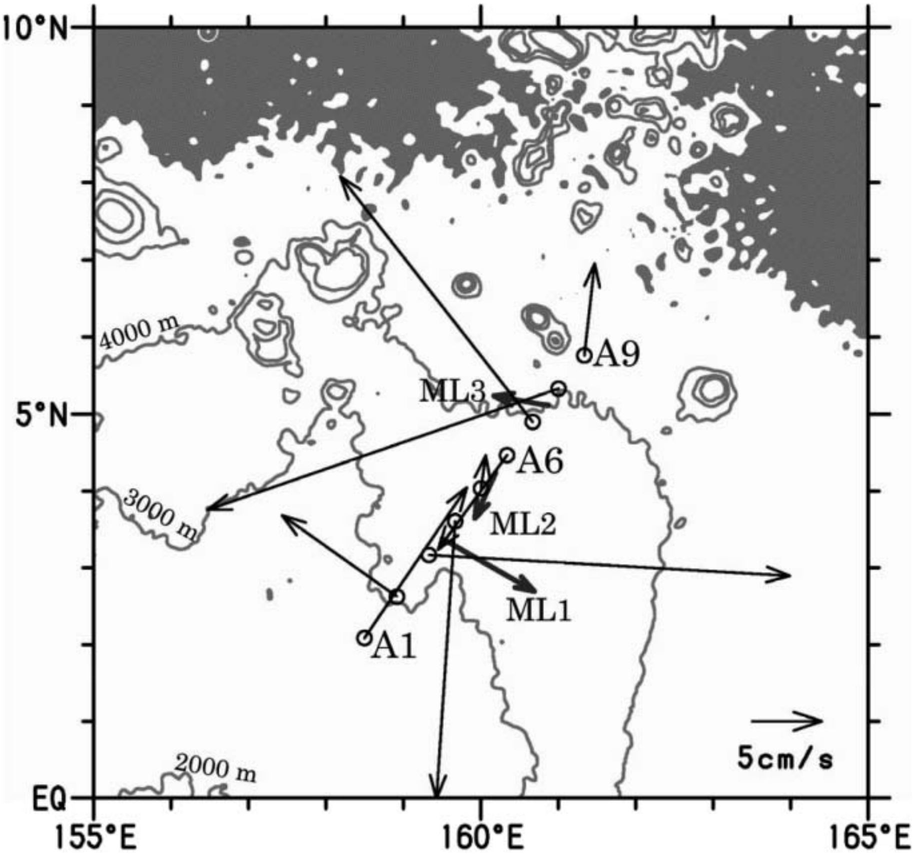


Fig. 2. Velocity vectors measured using LADCP at A1–A9 at depths of $\theta = 2.1$℃ (thin arrows) and current meters at depths of approximately 2000 m at ML1–ML3 averaged for the five-day period around the time of the LADCP observations (thick arrows). Contours are isobaths at 2000, 3000, and 4000 m. Shading represents areas at depths greater than 5000 m.

ADCP and to the bottom velocity estimated using sound pulses reflected from the sea bottom. Vertical shears of velocity were corrected to obtain a consistent profile of velocity using the fitted values. The barotropic tidal velocity estimated using the tide model of Egbert *et al.* (1994) was removed from the processed LADCP velocity. We also used LADCP echo-intensity data reflected from the third bin (12 m below the instrument).

The upper deep current was observed at three moorings: ML1 (located between A3 and A4), ML2 (between A5 and A6), and ML3 (between A7 and A8) (Kawabe *et al.*, 2006). The velocity data obtained from three current meters stationed at depths of 2170 m (ML1), 2150 m (ML2), and 1880 m (ML3) were temporally averaged for the five-day period around the day of LADCP observations; these average values were then compared with LADCP velocity.

## 3. Vertical structure of the upper deep current

Figure 2 shows velocity vectors from LADCP on an isothermal surface of potential temperature, $\theta = 2.1$°C, which is close to the top of the upper deep layer at a depth of approximately 2000 m (Kawabe *et al.*, 2003). The current is eastward at A3, southward at A4, northward at A5, southwestward at A6, northwestward at A7, and southwestward at A8. The vector mean of LADCP velocity between pairs of stations is southeastward for A3 and A4, southwestward for A5 and A6, and westward for A7 and A8.

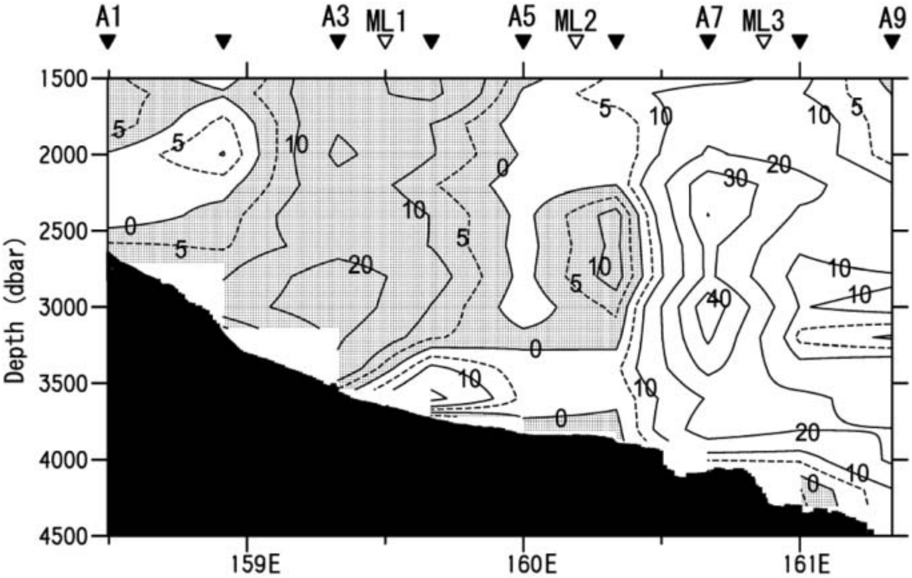


Fig. 3. Vertical sections of the velocity component (cm $s^{-1}$) perpendicular to the section measured at A1–A9 in the Melanesian Basin using LADCP. Shading represents a southeastward velocity. The barotropic tidal velocity estimated using the tide model of EGBERT (1994) was removed from the data. The LADCP stations are shown by solid triangles at the top of the panel. For reference, the mooring positions ML1–ML3 are shown by open triangles.

These current directions are similar to those measured using current meters at ML1, ML2 and ML3, respectively, although the amplitude of velocity is much larger. The southeastward current at ML1 and the westward current at ML3 are the countercurrent and the eastern core of the upper deep current, which continued for seven months during the first half of the mooring observation (KAWABE *et al.*, 2006). The northwestward current at A2 may represent the western core of the upper deep current inferred by KAWABE *et al.* (2006). These results demonstrate that the LADCP velocity data provide the correct direction of the velocity component perpendicular to the observation line.

The distribution of the perpendicular component of velocity (Fig. 3) indicates that the countercurrent has a great thickness at depths less than 3500 dbar and has a wide extent (159°–160°E), encompassing A3 and A4, with the maximum velocity of approximately 20 cm $s^{-1}$ recorded at A3. The observed large vertical extent of the countercurrent is consistent with the results of mooring observations undertaken at ML1, as described by KAWABE *et al.* (2006). The width of the countercurrent spans more than two intervals between the LADCP stations, which is larger than that speculated by KAWABE *et al.* (2006). The amplitude of velocity exceeds 10 cm $s^{-1}$ at every measurement depth and exceeds 20 cm $s^{-1}$ at 2000 dbar and 2700–3200 dbar. These values may represent an overestimate, although such a strong current may be possible over short time periods.

West of the countercurrent, a northwestward current core exists at depths between 1600 and 2500 dbar at 158.5°–159°E (A1–A2), with a maximum velocity of 10 cm $s^{-1}$ recorded at 2000 dbar at A2 (Fig. 3). This current likely represents the western core of the upper deep current. In contrast, the northwestward velocity at A7 represents the eastern core of the upper deep current. This may include a cyclonic eddy formed in combination with the countercurrent at A6. High velocities in excess of 30 cm $s^{-1}$ within the eastern core may partly reflect this eddy. The cyclonic eddy (or the countercurrent at A6) was not present in the current–

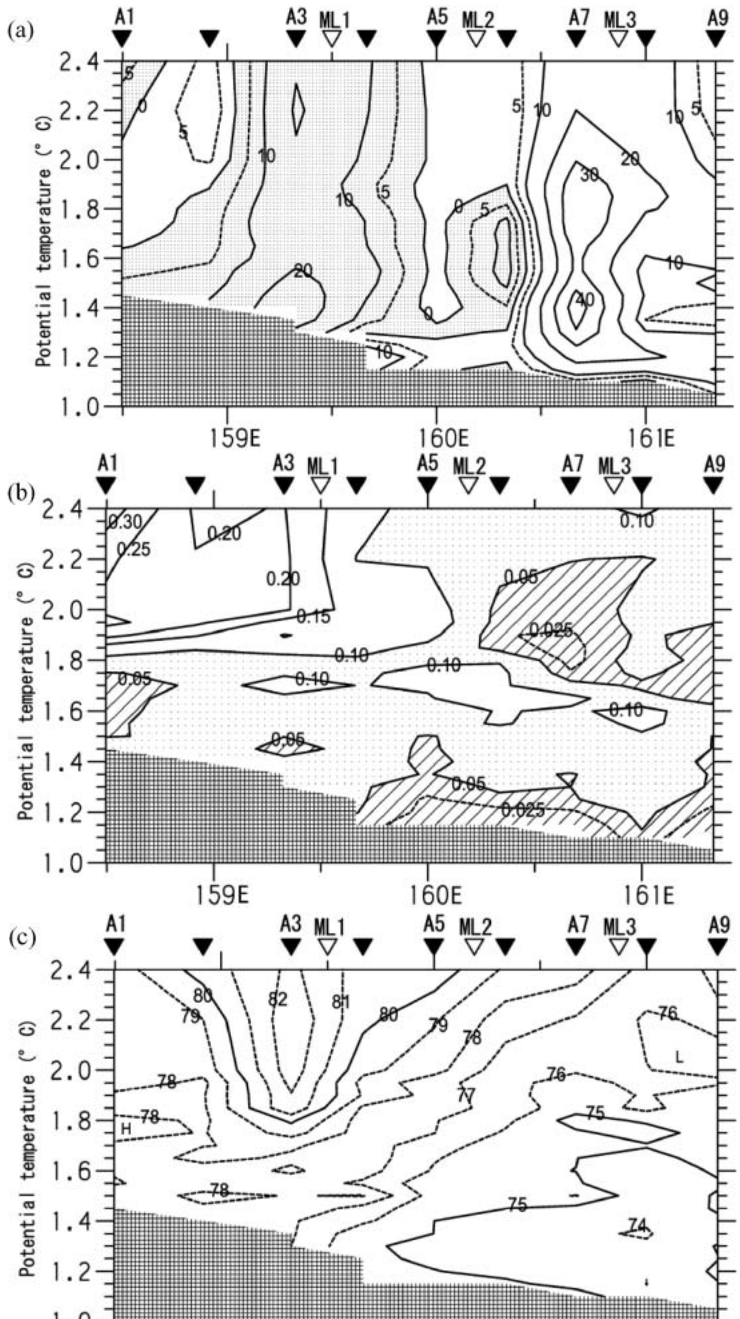


Fig. 4. Vertical sections at A1–A9 in the Melanesian Basin of the velocity component (cm $s^{-1}$) perpendicular to the section measured using LADCP (a), the anomaly on isotherms of dissolved oxygen (ml $l^{-1}$) derived from the average of values at A14–A17 (163.1°–164.3°E) as in KAWABE *et al.* (2003) (b), and echo intensity (dB) measured using LADCP (c). Potential temperature is taken as the ordinate. The hatched areas in the lower parts of (a) – (c) represent areas of no data due to the sea bottom. Shading in (a) indicates southeastward velocity. Areas of oblique lines and dotted areas in (b) indicate values of less than 0.05 and 0.10 ml $l^{-1}$, respectively.

meter results for the eastern core averaged during the first half of the mooring period; however, the current–meter data at 2650 m at ML2 show the countercurrent component around the time of the LADCP observation (KAWABE *et al.*, 2006). The structure of the eastern core of the upper deep current may be affected by the existence of an eddy (or small–scale countercurrent), but the location of the core is largely unaltered.

## 4. Characteristics of water carried by the deep currents

The western core of the upper deep current carries oxygen–rich water. This is especially pronounced in the upper part of the core above the 1.9°C isotherm, which has a large dissolved–oxygen anomaly of more than 0.20 ml $l^{-1}$, as determined from the averages at A14–A17 located at 8.0°–9.7°N, 163.1°–164.3°E in a small deep valley farther northeast of A9 (Fig. 4). The oxygen anomaly extends to A3, the center of the countercurrent, at depths shallower than the 1.9°C isotherm. The oxygen anomaly decreases markedly in the eastern part of the countercurrent to the east of A3. In the eastern core of the upper deep current, the anomaly is still positive but is relatively weak, occupying the upper part of the core. The oxygen anomaly in the lower part (below the 1.8°C isotherm) is almost uniformly weak in the western and eastern cores of the upper deep current and the intervening countercurrent.

Echo intensity is relatively strong in the upper part (above the 1.8°C isotherm) of the countercurrent, with the maximum intensity recorded at the center of the countercurrent. The intensity in the upper part of the countercurrent is much higher than that in the western and eastern cores of the upper deep current, being much higher than that in the eastern core. The highest echo intensity in the countercurrent and lowest in the eastern core are also seen in the lower part of the upper deep layer, although they are less pronounced than those in the upper part.

Thus, the differences in water–mass characteristics between the different currents are especially marked in the upper part of the currents (Fig. 5). The countercurrent contains

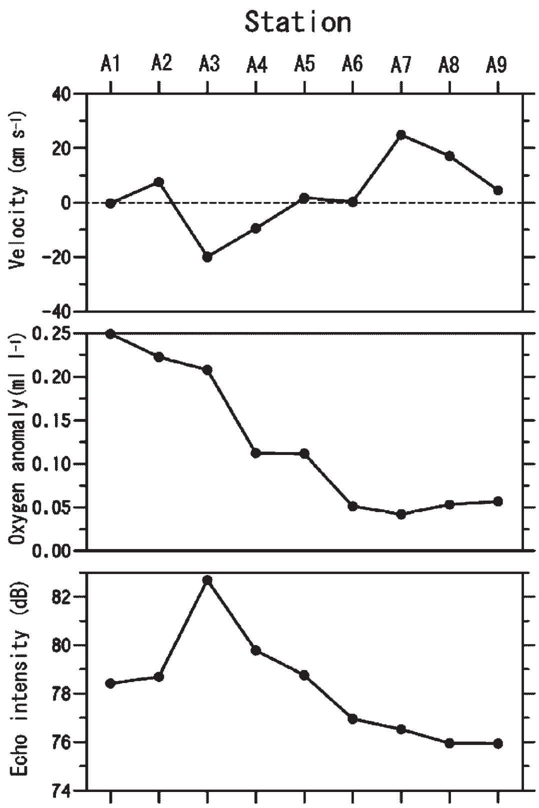


Fig. 5. Lateral distributions on an isotherm of $\theta = 2.1$℃ at A1–A9 in the Melanesian Basin of current velocity perpendicular to the observation section measured using LADCP (upper panel), the anomaly of dissolved oxygen from A14–A17 (middle panel), and echo intensity measured using LADCP (lower panel).

an intermediate oxygen anomaly between the eastern and western cores of the upper deep current. This suggests that the countercurrent carries a mixture of the UCPW carried by the two cores of the upper deep current; however, echo intensity in the countercurrent is much higher than that in the cores. This indicates that the countercurrent carries the upstream water, which is characterized by high echo intensity. If the countercurrent flows into the Melanesian Basin by proceeding along the 3000 or 3500 m isobaths, then the countercurrent in the upstream region must flow eastward along the southern boundary of the East and West Caroline Basins near the equator, carrying water with high echo intensity peculiar to the near–equator region. During eastward transportation, the water mixes with high-oxygen UCPW carried by the upper deep current.

FIRING *et al.* (1998) observed an eastward deep current at depths of 2000–3500 m at 0–1°S, 150°E on the southern boundary of the East Caroline Basin in August 1985 and January 1986. This eastward current may be steered into the Melanesian Basin by the bottom slope at a depth of approximately 3500 m, thereby becoming the countercurrent observed in the present study. The equatorial eastward current, however, was not found at 146°E in October 1993 (FIRING *et al.*, 1998). This may imply that the equatorial eastward current on the bottom slope is not always present. Even if the equatorial eastward current is always present, it does not detour around the Solomon Rise when it is detached from the bottom slope at the change in vertical structure. In such a case, the current probably continues eastward along the equator. The absence of the countercurrent on the Solomon Rise during the second half of the mooring observation described by KAWABE *et al.* (2006) may reflect the disappearance of the equatorial eastward current or the release of the current from topographic controls.

## 5. Conclusions

Current velocity and echo intensity were measured using LADCP over the northeastern slope of the Solomon Rise in the Melanesian Basin. We used these data to clarify the structure of the western and eastern cores of the upper deep current and the countercurrent at depths of 2000–3500 m. We used the echo intensity and dissolved oxygen characteristics of the water to infer the upstream pathway of the countercurrent.

The western core of the upper deep current was observed at depths of 1600–2500 dbar over the bottom slope, at water depths of approximately 3000 m, carrying UCPW with very high dissolved oxygen. The eastern core was observed in the eastern region over the bottom slope at water depths of approximately 4000 m. Between these two cores of the upper deep current, a thick countercurrent flowed with a large width of more than 100 km.

The countercurrent is located over the bottom slope at water depths of approximately 3500 m, carrying water that is characterized by extremely high echo intensity. Based on these facts, we inferred that the equatorial eastward deep current along the southern boundary of the East Caroline Basin, as observed by FIRING *et al.* (1998), is steered by the bottom slope at water depths of approximately 3500 m. This current is connected to the countercurrent within the Melanesian Basin observed in the present study.

The equatorial water carried by the equatorial eastward current mixes with high-oxygen UCPW carried by the upper deep current. This explains the fact that the water in the countercurrent has an oxygen content that is intermediate between that of the western and eastern cores of the upper deep current. Moreover, the long-time disappearance of the countercurrent in the Melanesian Basin (KAWABE *et al.*, 2006) may occur when the equatorial eastward current disappears or detaches from the bottom slope.

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