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Eastward Flows of the South Equatorial Central Pacific

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ABSTRACT

Data obtained during the Hawaii-to-Tahiti Shuttle Experiment in the central Pacific from the Equator to 17°S are used to study the variability of the two eastward flowing currents in the area: the South Equatorial Countercurrent (SECC), and the South Subsurface Countercurrent (SSCC). The meridional position of the SECC varies between 7 and 14°S, and its transport is affected by the wind stress west of 160°W. In contrast to observations in the eastern Pacific, the SSCC shows seasonal variations and extends as far south as 10°S in austral winter.

1. Introduction

The existence of eastward flows in the Equatorial South Pacific has often been described from geostrophic calculations. Previous works, reviewed below, indicate the existence of at least two types of currents, a shallow one around 10°S and a stronger one below the thermocline at about 5°S.

However, because of the randomness in space and time of the measurements, questions arose concerning the continuity of the flows throughout the ocean, and their variability. In particular, important variations in the hydrology and transport of the surface current were described. The subsurface countercurrent, although well defined eastward of 130°W, was not shown to be well separated from the Equatorial Undercurrent in the Western Pacific.

The first evidence of what was named the South Equatorial Countercurrent (SECC) was given by Reid (1959, 1961). His data indicated a subsurface eastward current from 165°E between 2 and 5°S to 95°W and between 10 and 14°S at depths of 300–400 m. At the sea surface, the data indicated an eastward flow between 169 and 135°W at 9°S. An eastward flow in the extreme east Pacific was found later in austral summer (Wooster, 1961) at 95°W, and between 5 and 8°S with maximum velocity at a depth of 100–200 m. In the western Pacific, Jarrige (1968) found an eastward flow at 170°E, around 10°S, extending from the surface to 500 m depth, corresponding to a minimum in surface salinity (34.0–34.8‰), in contrast to the reports of Reid and Wooster that the deeper flow was associated with a tongue of higher salinity (>34.9‰). Hence Jarrige suspected the possibility of the existence of two different eastward currents. From earlier measurements at 172°W, Tsuchiya (1968) independently raised the same question in spite of a different hydrology, proposing a shallow, saline current near 8°S and a deeper and less saline one at 5°S.

In the eastern Pacific, from the results of the *Eastropac* cruises between 126 and 86°W, Tsuchiya (1975) showed the existence of an eastward relatively stable current between 4 and 8°S and at depth from 150–250 m with a transport of $\sim 4 \times 10^6$ m^3 s^{-1}. The *Eastropac* atlas (Love, 1971) also shows a weak and variable shallow flow at 8–10°S, different in its hydrology from the deep current. Following Tsuchiya, we call the shallow and deep flows South Equatorial Countercurrent (SECC) and South Subsurface Countercurrent (SSCC), respectively.

The zonal extension of the SECC is subject to controversy. Although previous authors generally supposed a continuous surface flow throughout the Pacific, Donguy *et al.* (1976) showed the possibility of two different systems of eastward surface currents 1) two low-salinity (<35.5‰) flows at 10° and 18°S, west of 160°W extending from the Coral Sea; and 2) one higher-salinity (>35.5‰) flow at 10°S and 150°W. The South Subsurface Countercurrent, distinct from the Equatorial Undercurrent (EUC) in the Eastern Pacific, is, however, joined to it at 170°E (Hisard and Rual, 1970). At 170°W it was found to reach the surface at 5°S (Donguy *et al.*, 1974).

In this study we use part of the measurements obtained during the Hawaii-to-Tahiti Shuttle Experiment from 5 to 17°S and along three meridians: 150, 153, and 158°W. These data provide, for the first time, a regular coverage of the hydrology of this region for more than one year, and allow more precise determination of the spatial (both depth and latitude)

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distribution, and the seasonal variability of the eastward flows in the South Equatorial Pacific.

2. Data

Details concerning the organization of the Experiment and the tracks followed in each cruise are given by Wyrtki *et al.* (1981). Of the 15 cruises of the Experiment, 14 covered the South Pacific from the equator to 17°S, all at 150°W, from March 1979 to May 1980. Temperature and salinity data from CTD measurements (Williams, 1981) are used to compute dynamic height differences and geostrophic velocities between stations 1° apart, relative to 1000 db. Velocities are computed every 10 db from 0–1000 db, poleward of 2° latitude because the geostrophic calculations become less precise toward the equator. Zonal volume transport is given by integration over depth, excluding all zonal velocities less than 5 cm s^{-1} in magnitude, in order not to overestimate transport. Large zones of very weak geostrophic flow (1–2 cm s^{-1}) found by calculation are indeed not significant but by integration would lead to an important error in transport. Table 1 gives the principal results of these geostrophic calculations.

In addition, AXBT temperature data from 30 of the 35 Shuttle Experiment trans-equatorial flights along 150, 153, and 158°W (Stroup *et al.*, 1981) are used together with salinity from average *T–S* relationships to compute geostrophic velocities relative to 300 db. However, as the profiling-current-meter data (Firing *et al.*, 1981) show that currents of the order of 5 cm s^{-1} are often present at 300 db, these calculations are not sufficiently accurate to determine absolute velocities and transport. They can only be useful to indicate the variability of the surface flow. Seven-day averaged wind velocity and direction obtained from satellite measurements of cloud velocity during the same period over the South Pacific from 170°E to 130°W are used to assess the importance of local wind stress in the variability of surface currents (Sadler and Kilonsky, 1981).

3. Average flow pattern

The temperature and salinity sections and the geostrophic velocities from 12 cruises, from the end of March 1979 to the beginning of March 1980, are averaged to obtain the mean hydrology and patterns of the currents of this period. These mean sections are given in Fig. 1. The most important feature in the temperature structure (Fig. 1a), is variation of the thermocline with latitude; its upper and lower boundaries can be characterized by the 26 and 14°C isotherms, respectively. North of 3°S the presence of the equatorial upwelling and presence of the Equatorial Undercurrent below contribute to a spread of the thermocline. Southward, the 26°C isotherm varies from 90 m at 3°S to 120 m at 8°S and rises again to 90 m at 17°S. The 14°C isotherm has a pronounced downslope from 180 m at 3°S to 350 m at 17°S, which induces a regular southward widening of the thermocline. At the surface a thick mixed layer of water warmer than 28°C is found; this warm layer reaches 80 m at 8°S and is the cause of the trough in the 26°C isotherm. This vertical distribution is typical of the South Pacific.

The 35.0‰ isohaline (Fig. 1b) follows almost exactly the path of the 14°C isotherm. Above it extends a tongue of high-salinity water, which is characteristic of the waters carried below the surface by the South Equatorial Current (Tsuchiya, 1968). Below the thermocline the patterns of temperature and salinity are similar, characterized by a northward widening of the isotherms and isohalines, especially important north of 5°S.

TABLE 1. Results of geostrophic calculations of the SECC and SSCC.

		SECC			SSCC			
Shuttle cruise number	Date of section at 150°W	Latitude of main branch (deg S)	Maximum velocity (cm s^{-1})	Transport (10^6 m^3 s^{-1})	Latitude of main branch	Depth of upper 5 cm s^{-1} isotach (m)	Maximum velocity (cm s^{-1})	Transport (10^6 m^3 s^{-1})
2	23–28 Mar 1979	13–14	18	2.8	3°–4°S	170	34	6.8
3	3–9 Apr 1979	11–12	9	2.5	3°–4°S	180	16	5.8
4	3–9 Jun 1979	12–13	10	2.7	4°–5°S	180	18	8.9
5	17–24 Jun 1979	12–14	9	2.1	3°–4°S	160	27	19.5
6	9–15 Aug 1979	12–13	16	3.2	4°–5°S	160	20	13.1
7	17–23 Aug 1979	13–14	8	1.7	6°–7°S	200	13	7.4
8	23–29 Oct 1979	9–10	11	1.9	6°–7°S	220	10	5.1
9	1–5 Nov 1979	8–10	15	6.2	4°–5°S	180	16	2.1
10	28 Dec–3 Jan	9–10	9	2.7	5°–6°S	180	14	6.0
11	8–13 Jan 1980	10–12	9	1.5	6°–7°S	260	7	1.6
12	9–15 Mar 1980	11–13	18	4.0	5°–7°S	220	10	4.9
13	17–23 Mar 1980	7–9	20	4.6	6°–7°S	220	18	7.5
14	8–14 May 1980	9–10	12	2	—	—	—	0.0
15	18–23 May 1980	16	9	<1	6°–7°S	220	14	7.4

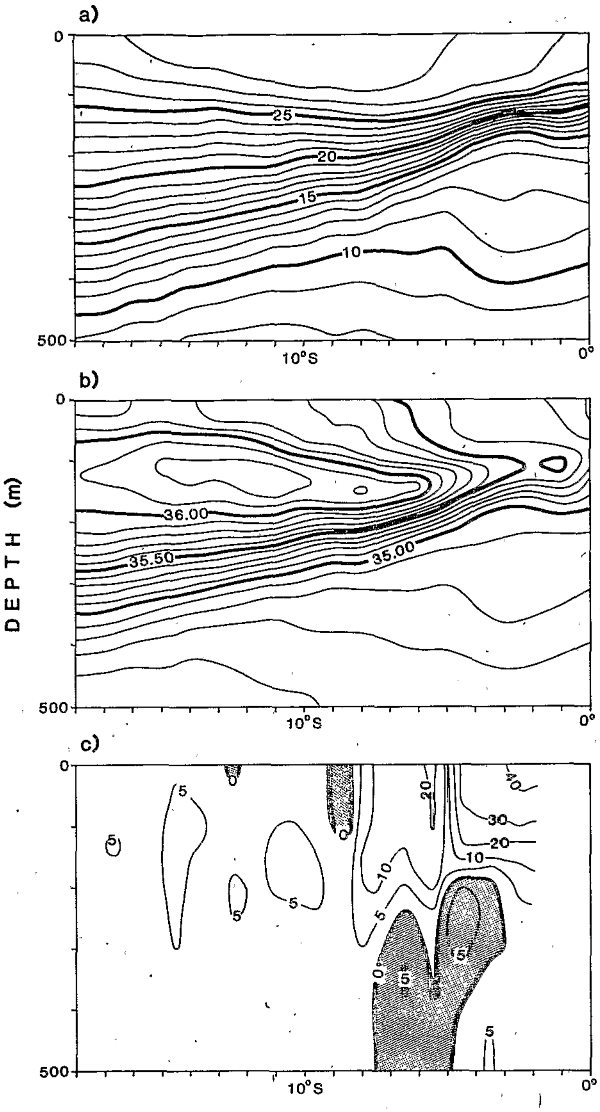

FIG. 1. (a) Temperature, (b) salinity from CTD measurements and (c) geostrophic velocity relative to 1000 db, averaged for 12 cruises at 150°W from March 1979 to March 1980. Zones of eastward flow are shaded. Velocities in cm s^{-1}.

On the averaged geostrophic velocity section (Fig. 1c), the South Equatorial Current is found to extend to at least 17°S. Most of its flow is, however, concentrated north of 8°S. The mean SECC appears only south of this latitude, composed of two thin branches of about 1° width, the more important at 8–9°S, 120 m thick; another at 12°S only 30 m thick.

The mean eastward geostrophic velocities are very weak, less than 5 cm s^{-1} in the surface flow. As shown in Table 1, the latitudes of the SECC, and in a lesser way of the SSCC, vary in time; thus, at a given latitude the flow fluctuates from eastward to westward, leading to low annual average values. The eastward transports, however, are computed for each cruise for the corresponding current position and then averaged. This calculation leads to a SECC annual mean transport of 3×10^6 m^3 s^{-1}.

The flow of the SECC is restricted to the surface mixed layer and therefore is not associated with a significant variation in temperature; its range of salinity is from 36.0–36.3‰. Thus, on an annual average, the hydrology of SECC waters is not very different from the hydrology of those carried by the surrounding South Equatorial Current.

Below the thermocline, the SSCC extends from 3 to 8°S, its upper boundary following roughly the slope of the 14°C isotherm, descending southward from 200 to 240 m. Below 500 m, the average velocity is not significant, less than 1 cm s^{-1}. Individual cruise sections show that the 5 cm s^{-1} isotach can reach 600 m when the current is strongest, but its main flow is always situated above 400 m. Its annual mean transport is 7.4×10^6 m^3 s^{-1}.

Between 220 and 350 m, the core of the SSCC corresponds clearly to an inversion in the slope of the 10–12°C isotherms. The same inversion of the slope of the 34.8‰ isohaline, at the base of the core, indicates that north of 5°S the current carries water slightly more saline than the average. However, the main contribution to the density anomaly at the origin of the eastward geostrophic flow comes from the northward increase in temperature, reflected by the inversion of the slope of the isotherms. This inversion was present during all the observed sections.

4. Seasonal variation

Because the SECC transport is small, always less than 7×10^6 m^3 s^{-1}, the computed transport is not accurate and small fluctuations cannot be easily resolved. However, some features appear on a time-series of the eastward transport computed from CTD measurements, relative to 1000 db (Fig. 2a). The SECC transport computed from AXBT measurements relative to 300 db (Fig. 2b) is not reliable in absolute value, for the reasons explained before. Moreover, there is an evident lack of coherence between the three AXBT sections. This can be attributed to an important short-term variability of the hydrological variables. This variability is partly smoothed by CTD sections, which take a few days, instead of a few hours for AXBT sections.

From March to the beginning of August 1979, the surface flow stays below its average value of 3×10^6 m^3 s^{-1}. Although the surface flow presents several branches, the most important one remains south of 11°S. After August it moves slowly northward reaching 8–10°S at the beginning of November 1979 when its transport is maximum.

As the flow weakens, it is again found south of 9°S in January 1980. A secondary maximum is reached in March 1980. This time the flow is strong, first at 12°S and a week later at 8°S. At the end of May 1980

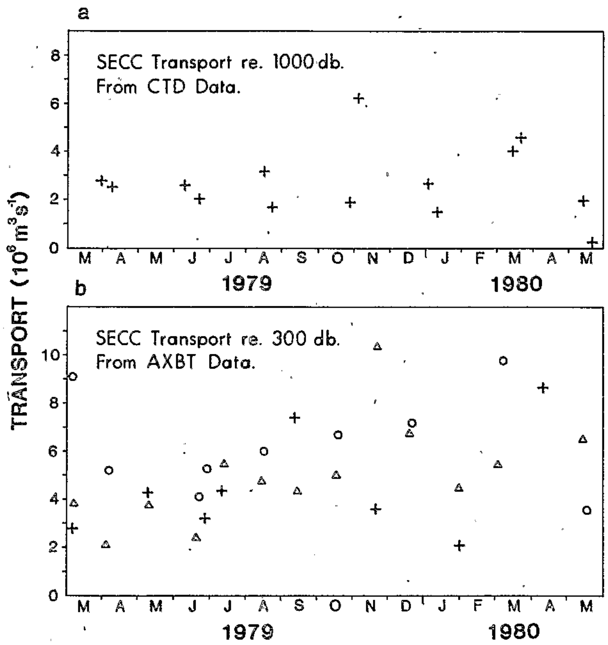

FIG. 2. (a) Time series of geostrophic transport of the SECC relative to 1000 db computed from CTD temperature and salinity data during 14 cruises of the Hawaii-to-Tahiti Shuttle Experiment at 150°W. (b) Time series of geostrophic transport of the SECC relative to 300 db computed from AXBT temperature measurements made during 30 flights of the Hawaii-to-Tahiti Shuttle Experiment and *T–S* relationship. Symbols: plus, 150°W; triangles, 153°W; circles, 158°W.

the eastward surface flow disappears north of 14°S and reappears south of 16°S, at the limit of the measurements, thus not allowing us to give a precise value for its transport at this time. A characteristic seasonal behavior cannot be inferred from the transport time series. The large transport fluctuations in time and space suggest the contribution of eddies detached from the SEC to the SECC flow. This contribution is impossible to evaluate quantitatively. But the most important point is the permanence, south of 7°S, of some eastward geostrophic transport, which is not a mere fluctuation of the SEC. Moreover, we may note that the two maxima in the flow do occur in austral summer, when the trade winds are usually weak.

The satellite cloud-motion measurement charts (Kilonsky, personal communication, 1982) show that west of 150°W, the trade winds blow regularly between the east-northeast and the east-southeast, with weekly mean speeds from 5–10 m s^{-1}. This pattern is severely perturbed only three times during the Shuttle Experiment.

During the second half of October 1979, in the whole area from 5–15°S and west of 155°W to 170°E, the trades weaken and are replaced by slow and variable winds from southwest to northwest; they regain their previous strength only in mid-November. In mid-December 1979 a strong northwest monsoon extends for a week to 160°W, south of 10°S, and is followed by another week of variable winds. From 20 January to 15 February 1980 the region west of 155°W is again subject to variable winds from the west sector.

The SECC flow maximum at the beginning of November 1979 is possibly associated with the corresponding weakening of the trades, but there is no flow increase in December 1979 and January 1980, after the monsoon had been strongest. There were no cruises in February 1980, during the other period of weak trades, but a strong SECC flow exists in March 1980.

Thus, location of the flow of the SECC does not seem to be tied clearly to the strength of the westerly winds, and a weakening of the westward wind stress west of 155°W appears to contribute to an increase in its transport at 150°W, after a delay of two to three weeks.

The surface temperature in the main branch of the SECC remains at more than 29°C until the beginning of June 1979 and then decreases to between 28 and 29°C until January 1980 when it again increases above 29°C. Therefore, the principal flow of the SECC always stays in the patch of warmer water south of 6–7°S, and its temperature varies accordingly. When the current is at a maximum, however, as in November 1979, its deepest part reaches well inside the thermocline. Fig. 3 shows the hydrology and geostrophic flow when the SECC is at this maximum in transport and meridional extension. During the 14 cruises, the salinity of the surface waters carried by the SECC varies in a wide range from 35.3 to 36.1‰. That variation can be explained by following the evolution of the field of salinity south of 7°S. The tongue of high salinity corresponding to the westward flow of the SEC, as shown in Fig. 1b, is indeed not constant in depth and thickness. The upper part of the 36.0‰ isohaline stays at 100 m depth from March to the beginning of June 1979. Then it rises progressively from the south, and the mean surface salinity south of 10–11°S remains above 36.0‰ until at least November 1979. The next cruise, in January 1980, shows that this isohaline is again below 50 m and remains between 50 and 100 m until the last cruise in May 1980. During 10 of the 14 cruises studied, the SECC is characterized by a surface salinity lower than that of the surrounding SEC water. The difference is generally slight, 0.1–0.3‰, but reaches 0.5‰ in March 1980 when the SECC transport is at a maximum. During the four cruises where the SECC does not correspond to a minimum of salinity in April and May 1979, and in May 1980, the tongue of high salinity is at its deepest position, and the eastward flow is located in a zone of salinity gradients.

Thus, as the branches of the SECC are thin and weak, and doubtless subject to much mixing and evaporation, the salinity of the current is perturbed

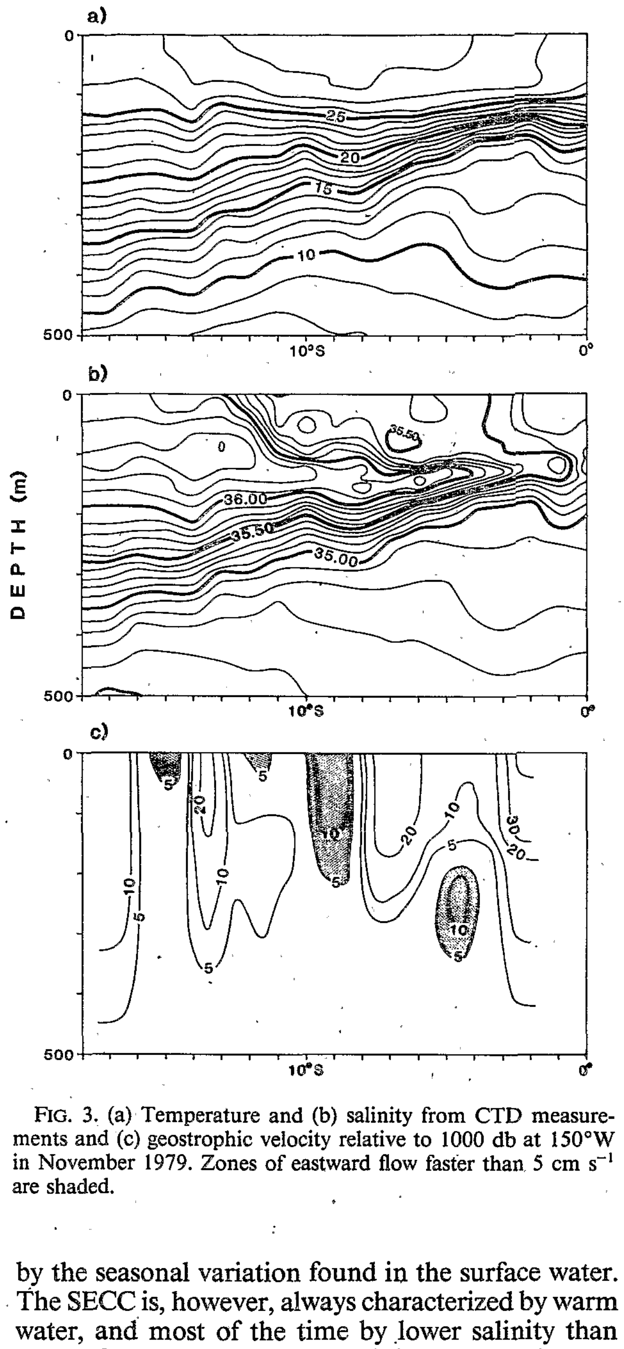

FIG. 3. (a) Temperature and (b) salinity from CTD measurements and (c) geostrophic velocity relative to 1000 db at 150°W in November 1979. Zones of eastward flow faster than 5 cm s^{-1} are shaded.

by the seasonal variation found in the surface water. The SECC is, however, always characterized by warm water, and most of the time by lower salinity than the SEC water. This lower salinity may be in part caused by the heavy rainfall associated with the Intertropical Convergence Zone in austral summer. But the SECC is also characterized by a relative minimum of salinity in austral winter.

In contrast of the SECC, the position of the SSCC fluctuates little around its average value given in Fig. 1, and its transport is generally larger and more variable (Fig. 4). In March and April 1979 it is composed of two cores, the more important at 3–4°S and between 170 and 500 m, and the other, thinner, at 6–7°S and slightly deeper. Its transport is $\sim 7 \times 10^6$ m^3 s^{-1} and rises to a maximum of 19.5×10^6 m^3 s^{-1} in June 1979 after a third branch appears between 9 and 10°S and 400 m deep. At least two of the three flows are clearly marked by a northward downslope of the isotherms below 14°C and of the isohalines 34.6–34.9‰, indicating that they carry water warmer and slightly more saline than the surrounding water (Fig. 5). Its transport then decreases until November 1979 when only the northernmost branch subsists with a low value of 2×10^6 m^3 s^{-1}.

During the subsequent cruises, transport of the SSCC varies from 2×10^6 to 7.5×10^6 m^3 s^{-1} and disappears totally at the beginning of May 1980, when an eastward surface flow appears from 4–6°S for only a few weeks. For three cruises, in April, August and October 1979, the current clearly extends north of 2°S and is, therefore, joined to the Equatorial Undercurrent (EUC). A thin flow (less than 1° wide) seems to link the SSCC to the surface at 4°S, through the thermocline, in August 1979 and January 1980. Because this flow is not indicated in the field of temperature and salinity as is the SSCC, it is probably only a temporary perturbation of the surface westward flow. The maximum in transport observed in July 1979 could in itself be only a transient, nonreproducible event. But we note that most of the other cruises carried out in austral winter also show a transport of the SSCC above the average.

Thus, the results of most of the cruises show that the SSCC is located closer to the Equator, and presents an increase in transport during austral winter, and that its core is associated with a relative maximum of salinity below the thermocline.

5. Discussion and conclusion

The above results present some new information on the kinds of eastward flows found in the Equatorial South Pacific. The successive cruises of the Hawaii-to-Tahiti Shuttle Experiment at 150°W show that the SECC is indeed characterized by warm water of salinity that is often lower than that of the water carried by

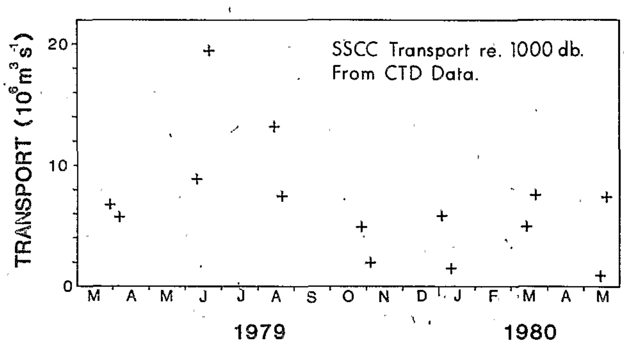

FIG. 4. Time series of geostrophic transport of the SSCC relative to 1000 db from the same data as in Fig. 2a.

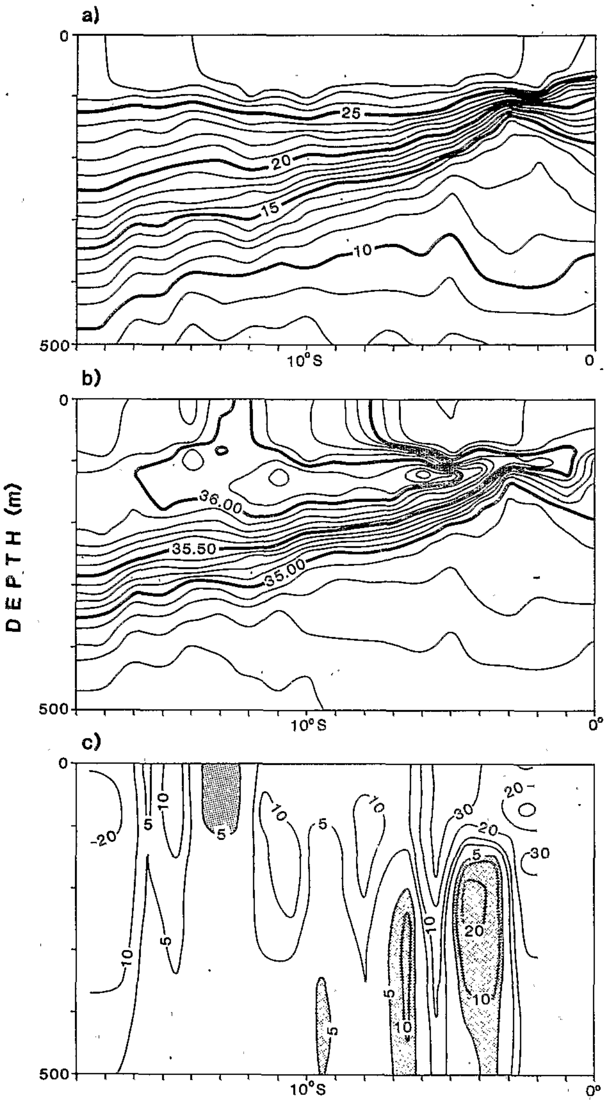

FIG. 5. (a) Temperature and (b) salinity from CTD measurements and (c) geostrophic velocity relative to 1000 db at 150°W in June 1979. Zones of eastward flow faster than 5 cm s^{-1} are shaded.

the surrounding SEC in the central Pacific. Previous measurements in the same area (a review of them given by Donguy *et al.*, 1976) did not clearly reveal this feature because of the high variability in time of the flow's hydrology. The SECC transport increases when the eastward wind stress disappears west of 155°W. But the current at 150°W is not changed by strong northwest winds west of 160°W.

In the eastern Pacific between 120 and 86°W, a surface eastward flow was found associated with a pool of warm water and a range of salinity from 34.5 to 35.7‰ (Love, 1971). This flow also seems to be observed only when the trade winds are the weakest, in austral summer (Tsuchiya 1974). This similarity with the current at 150°W suggests a possible temporary continuity of the SECC from the central Pacific to the area west of South America. In the western Pacific (west of 170°W), the eastward flow is more steadily associated with a tongue of low salinity (<34.8‰) originating in the northern Coral Sea (Jarrige, 1968; Merle *et al.*, 1969). A discontinuity in the surface dynamic topography between 170 and 180°W, well marked in July 1970, and the difference in hydrology of the eastward flow on each side of this meridian led Donguy *et al.* (1976) to the hypothesis of the existence of two separated gyres of opposite circulation in the South Pacific. Our study cannot confirm this hypothesis; favorable conditions for a link between the two eastward flows exist, however, in austral summer, when eastward wind stress appears west of 160°W.

In the eastern Pacific, the SSCC was found to be relatively stable, with a mean transport of $\sim 5 \times 10^6$ $m^3\ s^{-1}$, and to vary in location between 3 and 6°S (Tsuchiya 1975). At 150°W its behavior is quite different with a higher mean transport ($8 \times 10^6\ m^3\ s^{-1}$), but an important variability around this mean value from 1×10^6 to $20 \times 10^6\ m^3\ s^{-1}$. It is also joined to the EUC for short periods, as was observed in the western Pacific (Hisard and Rual, 1970). It shows a seasonal behavior with maximum flow in austral winter, when it extends to 10°S. A similar seasonal variation appears, though less marked, in the transport computed from direct current measurements of the EUC during the Shuttle Experiment (Wyrtki *et al.*, 1981), supporting the hypothesis of a common origin of the EUC and SSCC suggested by Hisard and Rual (1970) and Tsuchiya (1975).

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