

Western boundary currents and transports off French Guiana as inferred from *Pegasus* observations

Currents
Temperature
Salinity
Western boundary
Equatorial Atlantic

Courants
Température
Salinité
Bord Ouest
Atlantique équatorial

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Received 20/07/93, in revised form 30/11/93, accepted 7/12/93.

ABSTRACT

Pegasus current measurements carried out along a section located off French Guiana are presented; the section was repeated five times from September 1989 to June 1991 during the NOE (région Nord-Ouest équatoriale)/STACS (Sub Tropical Atlantic Climate Studies) cruises on board the NOAA (National Oceanographic and Atmospheric Administration) research vessels. The data (vertical and horizontal distributions) show, as suggested by earliest observations, the presence of different currents. At the surface, and in winter, the North Brazil Current (NBC) flows northwestward (positive), is strong (120 cm/s), confined in the first 250 m, coastally trapped (within 250 km) and fed by offshore waters; in summer the NBC strengthens (the velocity increases to 150 cm/s), vertically extends (down to 800 m) and veers offshore; the mean NBC mass flux computed from all the sections available is 34 ± 9 Sv with absolute maximum and minimum respectively in September 1989 (81 ± 4 Sv) and February 1990 (13 ± 1 Sv). Subsurface, a southeastward (negative) undercurrent (herein after named Western Boundary UnderCurrent) is present in winter-spring and located in the layer 250-800 m with similar velocities in February 1990 (-33 cm/s) and June 1991 (-29 cm/s) but with largest vertical and horizontal extensions in the latter case; in summer (September 1989 and September 1990) this undercurrent is absent; the mean WBUC mass flux is -9 ± 3 Sv; the maximum is observed in June 1991 (-19 ± 2 Sv) and the minimum in February 1990 (-3 ± 0.4 Sv) and January 1991 (-5 ± 1 Sv). Deeper, the equatorward Deep Western Boundary Current is trapped against the continental shelf (within 100 km of the shelf break), extends downward from 1 200 to 3 000 m depth with the velocity core centred in the 1 700-2 000 m layer, is maximum (-50 cm/s) in spring-summer and minimum (-23 cm/s) in winter; the absolute velocity (-92 cm/s) has been recorded at 2 000 m depth in September 1989 suggesting a strong variability at this level; the mean equatorward DWBC mass flux is -30 ± 14 Sv with absolute maximum and minimum respectively in September 1989 (-59 ± 6 Sv) and September 1990 (-7 ± 1 Sv). The Integrated Mass, Temperature and Salt Fluxes (IMF, ITF and ISF) with the cumulated errors, computed across the whole section and down to 3 000 m depth for the September 1990, January 1991 and June 1991 cruises, are all positive in September 1990 (respectively 1.9 ± 19 Sv, 3.1 ± 30.1 PW and $74 \pm 1 845$ Tt/s) but all negative both in January 1991 (-13.3 ± 17.0 Sv, -15.6 ± 26.5 PW and -478 ± 1594 Tt/s) and June 1991 (-3.8 ± 10.1 Sv, -4.0 ± 16.3 PW, -130 ± 989 Tt/s) showing a strong variability between the summer and winter periods. The mean IMF, ITF and ISF values (respectively -5.1 ± 46.4 Sv, -5.2 ± 73 PW and -178 ± 4428 Tt/s) are high and negative, indicating the large influence of the DWBC and the associated North Atlantic Deep Water (upper part) off French Guiana at 5°N .

Oceanologica Acta, 1994. 17, 2, 143-157.

15 NOV. 1994

O.R.S.T.O.M. Fonds Documentaire

N° : 40719

Cote : B Ex 1

RÉSUMÉ

Les courants limites de bord ouest et les transports associés au large de la Guyane française déduits des observations *Pegasus*

Des observations de courant effectuées au *Pegasus* en face de la Guyane française de 1989 à 1991 ont permis une approche des variabilités intra-annuelle et inter-annuelle associées aux courants limites de bord ouest. Ces courants, en dépit de leur très grande importance pour les échanges inter-hémisphériques, tant en surface, subsurface que profondeur, avaient été paradoxalement peu étudiés entre l'équateur et la latitude 8°N. Dans cet article sont présentés les résultats de courant obtenus le long d'une radiale située en face de Cayenne et occupée en septembre 1989, février et septembre 1990, janvier et juin 1991 dans le cadre du programme conjoint franco-américain NOE (région Nord-Ouest Équatoriale)/STACS (SubTropical Atlantic Climate Studies) à bord de navires océanographiques de la NOAA (National Oceanographic and Atmospheric Administration). Ces résultats, en accord avec les mesures obtenues antérieurement (dérive des bateaux marchands et trajectoires des bouées dérivantes SEQUAL/FOCAL), montrent la présence en surface du Courant Nord Brésilien (CNB), portant au nord-ouest (positif) et caractérisé par une variabilité intra-annuelle marquée : en hiver boréal, le CNB est fort (120 cm/s), confiné dans les 250 premiers mètres, collé à la côte (distance n'excédant pas 250 km de la pente du plateau continental) et alimenté par les eaux du large ; en été, ce courant s'intensifie en surface (150 cm/s), a une extension verticale plus importante (0-800 m) et subit une « rétroflexion » vers le large suite au déplacement vers le nord de la Zone InterTropicale de Convergence des Alizés ; le flux moyen de masse associé au CNB et calculé sur l'ensemble des campagnes est de 34 ± 9 Sv, les flux maximum et minimum étant observés respectivement en septembre 1989 (81 ± 4 Sv) et février 1990 (13 ± 1 Sv). En subsurface, les résultats montrent la présence en hiver et au printemps d'un Sous-Courant de Bord Ouest (SCBO), portant au sud-est (négatif) dans la couche 250-800 m, avec des vitesses comparables en février 1990 (-33 cm/s) et en juin 1991 (-29 cm/s) ; c'est la première fois qu'un SCBO est observé dans cette aire océanique ; ce courant est absent en été (septembre 1989 et 1990) ; le flux de masse associé à ce sous-courant est maximum en juin 1991 (-19 ± 2 Sv) et minimum en février 1990 ($-3 \pm 0,4$ Sv), le flux moyen calculé sur l'ensemble des campagnes étant égal à -9 ± 3 Sv. Aux grandes profondeurs, le Courant Profond de Bord Ouest (CPBO), portant également au sud-est, est collé à la côte (distance n'excédant pas 100 km de la pente du plateau continental), situé dans la couche 800-4 000 m avec un noyau de vitesse centré entre 1 700 et 2 000 m de profondeur, maximum en été (-50 cm/s) et minimum (-23 cm/s) en hiver ; le maximum maximum de vitesse (-92 cm/s) a été enregistré en septembre 1989 à l'immersion 2 000 m ; la moyenne du flux de masse associé au CPBO sur l'ensemble des campagnes est de -30 ± 14 Sv, ce flux étant maximal en septembre 1989 (-59 ± 6 Sv) et minimal en septembre 1990 (-7 ± 1 Sv).

Les Flux Intégrés de Masse, de Température et de Sel (FIM, FIT et FIS) et les erreurs cumulées associées ont été calculés sur toute la section (de la surface jusqu'à l'immersion 3 000 m) pour les radiales de septembre 1990, janvier 1991 et juin 1991. Ces flux sont positifs (vers le nord-ouest) en septembre 1990 (respectivement $1,9 \pm 19$ Sv, $3,1 \pm 30,1$ PW et $74 \pm 1\,845$ Tt/s) et négatifs (vers le sud-est) en janvier 1991 ($-13,3 \pm 17,0$ Sv, $-15,6 \pm 26,5$ PW et $-478 \pm 1\,593$ Tt/s) et juin 1991 ($-3,8 \pm 10,1$ Sv, $-4,0 \pm 16,3$ PW et -130 ± 989 Tt/s) ; ces résultats suggèrent la présence d'une variabilité marquée entre l'été et l'hiver. Les flux intégrés moyens de masse, de chaleur et de sel (respectivement $-5,1 \pm 46,4$ Sv, $-5,2 \pm 73$ PW et $-178 \pm 4\,428$ Tt/s) sont négatifs, soulignant l'importance des courants de sud-est et du maximum de salinité de l'Eau Profonde de l'Atlantique Nord (partie supérieure) en face de Cayenne.

Oceanologica Acta, 1994. 17, 2, 143-157.

INTRODUCTION

Oceanic heat flux has been shown to be an important component of the global energy balance (Vonder Haar and Oort, 1973). This heat flux is maximum at subtropical latitudes in the North Atlantic and the northward transport is mainly supported by low-latitude western boundary currents (Bryden and Hall, 1980). It has moreover been shown (Csanady, 1985; Johns *et al.*, 1990) that these boundary currents also play an important role in the recirculation of both the equatorial current system and the dynamics of the thermohaline circulation (below 1 000 m depth). Richardson and McKee (1984) found, from monthly mean merchant shipdrift distributions in the equatorial Atlantic, two different surface coastal flow patterns: 1) in boreal winter, when the Northeast trade winds regime prevails, a continuous western boundary current, North Brazil Current (NBC) and Guiana Current (GC), flowing from the equator to the Caribbean Sea; 2) in boreal summer, the retroflexion off French Guiana of a part (2/3 according to Csanady, 1985) of the NBC, feeding now the North Equatorial CounterCurrent (NECC); this phenomenon occurs under the Southeast trade Winds regime following the northward displacement of the InterTropical Convergence Zone (ITCZ) in May-June. This seasonal northwestern equatorial surface current scheme is, however, tempered by the SEQUAL (SEasonal eQUatorial AtLantic adjustment)/FOCAL (programme Français Océan Climat en zone équatoriale Atlantique) drifter trajectories obtained in 1983 and 1984 in this area (Richardson and Reverdin, 1987). If the agreement between the shipdrift and the buoy trajectories is quite good in boreal winter, in summer all the drifters veer seaward off Cayenne, inducing a cut-off in the coastal current system north of 6°N. Are these two schemes contradictory or simply the effect of an interannual variability at that time? Subsurface, the northwestern equatorial circulation (to the south of 3°N) was first inferred from hydrological and oxygen distributions (Metcalfe and Stalcup, 1967; Cochrane *et al.*, 1979) and later on from direct current observations (Flagg *et al.*, 1986; Johns *et al.*, 1990). All these observations show a permanent subsurface retroflexion phenomenon in this area. North of 3°N, Schott and Böning (1991) reported the existence of the equatorward Western Boundary UnderCurrent (WBUC), "more from indications than from observations". Is this undercurrent real, permanent or only present for a part of the year north of 3°N? Deeper, in the 1 000-3 000 m layer, the presence of the equatorward Deep Western Boundary Current (DWBC) was inferred at 26°30' N from geostrophy and freon 11 distributions (Fine and Molinari, 1988) and observed there later on from direct current measurements (Lee *et al.*, 1990). The offshore deep mooring measurements carried out further south at 8°30' N-52°09' W (Johns *et al.*, 1990) surprisingly show no indications of this deep equatorward flow not at 2 000 m depth, but much deeper (below 3 800 m depth). Is the DWBC absent at that latitude or are its width and velocity core there respectively smaller than the mooring offshore distance and deeper than the one observed further north?

To improve the description of the variability (seasonal and year-to-year evolution) of this complex flow pattern at all

depths in that area, *Pegasus* current measurements were carried out off French Guiana from 1989 to 1991. Individual (for each main current NBC, WUBC and DWBC) and integrated (across the whole section) mass fluxes and temperature and salt transports have been evaluated. The paper is organized as follows: technology and data are first presented, then the current results with associated and integrated transports are described, followed by discussion, a summary and the conclusions.

TECHNOLOGY AND DATA

The *Pegasus* is an acoustically tracked, free-falling profiler of horizontal current components (Spain *et al.*, 1981). The instrument used in this work is manufactured by Benthos. The 10 khz *Pegasus* transducer interrogates every sixteen seconds two fixed acoustic Benthos transponders deployed on the ocean floor in the direction of the mean current. Each transponder responds at its own frequency, setting in the range 11.5-13.0 Khz. The *Pegasus* records the acoustic travel times from the two transponders, together with temperature and pressure. During the cast, the instrument descends by the use of additional weights which are released either by a bottom trip mechanism or by a pressure release at a preassigned pressure (generally 3 000 dbar during this experiment). The mean vertical *Pegasus* speed is around 45 cm/s. At each station, the unique geometry of the transponder positions is obtained through an acoustic survey of the bottom units. A mean sound velocity profile, drawn from a Niel Brown CTD profile carried out at the same location during the *Pegasus* cast, is used to convert the acoustic travel times (seconds) into distances (metres). The horizontal coordinates at each pressure level are then determined and the horizontal velocity components computed. The data processing is performed on board with an IBM PC using a software provided by Benthos and improved by P. Vertès from the University of Miami. Previous operations showed the ability of such an instrument successfully to record ocean western boundary currents (Leaman *et al.*, 1987).

We present here the *Pegasus* observations made along a section located in front of Cayenne and repeated five times (September 1989, February 1990, September 1990, January 1991 and June 1991, hereinafter referred respectively to as S89, F90, S90, Ja91 and Ju91) during the NOAA (National Oceanographic and Atmospheric Administration) STACS (SubTropical Atlantic Climate Studies) cruises. The *Pegasus* section contains seven stations [NC2 to NC8 (fig. 1)]. The characteristics (time deployment, positions and depths of the acoustic transponders, length and orientation of the base line...) are summarized in Table 1. The data are reported in Colin *et al.* (1991 *a* and 1992 *a*). The N16 STACS *Pegasus* station at 10° N-49°02' W (the farthest station of the section) has been included in this study (courtesy of K. Leaman). Other direct current measurements (free-falling current profiler sliding along a vertical taut wire attached to a free-drifting surface float positioned by GPS) associated with hydrological observations carried out during the NOE (étude de la région Nord-Ouest Équatoriale atlantique) programme on board the

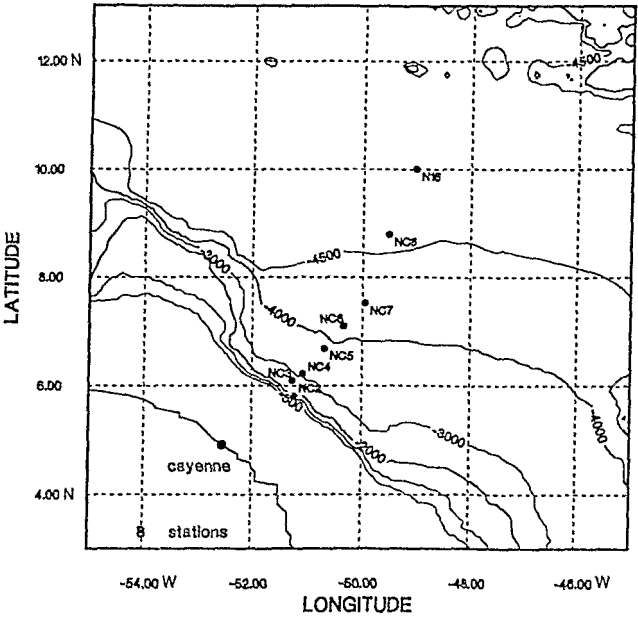


Figure 1
Geographical positions of the NOE/STACS current Pegasus stations along the "Cayenne" line from 1989 to 1991.
Position géographique des stations Pegasus effectuées le long de la radiale « Cayenne » dans le cadre du programme NOE/STACS de 1989 à 1991.

ORSTOM R.V. "André Nizery" (Colin *et al.*, 1990 and 1991 b), at the same period of time as the STACS programme, will be referred to in this paper. Recent satellite drifter trajectories obtained from October 1990 to February 1991 (courtesy of W. Brown) will complete the description of the seasonal variability of the currents.

Table 1
Pegasus station characteristics.
Caractéristiques des stations Pegasus.

STATIONS	2	3	4	5	6	7	8	16
Position	5° 49' N 51° 14' W	6° 06' N 51° 16' W	6° 13' N 51° 04' W	6° 41' N 50° 40' W	7° 06' N 50° 20' W	7° 31' N 49° 57' W	8° 47' N 49° 31' W	10° 00' N 49° 02' W
Date of deployment	February 1990	February 1990	September 1989	September 1989	September 1989	September 1989	September 1990	February 1990
Transponders frequencies (kHz)	12.5 and 12.0	11.5 and 12.5	12.5 and 11.5	12.0 and 11.5	12.5 and 12.0	12.5 and 11.5	12.0 and 12.5	12.5 and 12.0
Depth (m) of the transponders	1107 and 1185	2497 and 2479	2993 and 2993	3789 and 3736	4117 and 4110	4235 and 4235	4574 and 4571	4852 and 4852
Length (m) of the baseline (BL)	1097	2768	3357	3645	4247	3927	4242	4340
Orientation (θ°) of the baseline	- 130	51	- 124	- 140	- 137	- 136	90	91

The velocity measurement errors (Leaman and Vertes, 1983; Leaman *et al.*, 1987) are estimated from the inaccuracy of: the length (± 10 m) and orientation ($\pm 3^\circ$) of the transponders baseline, the depth (± 5 m) of the transponders, the *Pegasus* instantaneous depth (± 2 m) and the falling (or ascent) *Pegasus* rate (± 0.5 cm/s). The velocity measurement errors rarely exceed 15 % of the raw velocity values. When velocity values are missing at a station, they are either interpolated (between two consecutive profiles, at station NC8 in Ja91 for example) or extrapolated (at station NC2 in S90) through a bilinear procedure. These error sources will be discussed. The CTD data along the whole section are drawn from the NOAA STACS Cruise Reports 34-38 (courtesy of R.L. Molinari).

The mass (10^6 m³/s or Sverdrups) fluxes across the section have been computed using the following integral

$$\int_{z_1}^{z_2} [\Delta x \cdot \bar{U}_n] \cdot dz,$$

where dz , Δx and $\bar{U}_n$ indicate respectively the vertical increment positive upward, the distance between two consecutive *Pegasus* stations and the mean velocity component (positive northwestward) normal to each elementary surface delimited by two consecutive stations. The temperature (PetaWatts) and salt (10^6 kg/s or thousand*tons/s hereinafter Tt/s) transports have been evaluated through the following integrals:

$$\int_{z_1}^{z_2} [\Delta x \cdot C_p \cdot \bar{\rho} \cdot \bar{\theta} \cdot \bar{U}_n] \cdot dz$$

and

$$\int_{z_1}^{z_2} [\Delta x \cdot C_p \cdot \bar{\rho} \cdot \bar{S} \cdot \bar{U}_n] \cdot dz$$

where θ , S , ρ and C_p respectively indicate the potential temperature (in Kelvins) and salinity computed from two consecutive stations, the density and the specific heat capacity ($4190 \text{ J.kg}^{-1}.\text{K}^{-1}$).

The flux errors are computed from the previous integrals, using both the temperature ($\delta T = 0.02^\circ\text{C}$) and the salinity ($\delta S = 0.02$) CTD inaccuracy values. For the temperature flux for example the error is computed as follows:

$$C_p \int_{z_1}^{z_2} [\bar{\rho} \cdot \bar{\theta} \cdot \delta U_n + \bar{\rho} \cdot \bar{U}_n \cdot \delta \theta + \bar{\theta} \cdot \bar{U}_n \cdot \delta \rho] \cdot \Delta x \cdot dz$$

Despite the strong correlation between the mass, temperature and salt fluxes (the section is open so the mass flux is not balanced), they nevertheless provide information on the relative importance of the different water masses which are present in the area.

RESULTS

The vertical sections described in this paper show the alongshore (AL) and across-shore (AC) velocity components of the currents drawn from the *Pegasus* profiles. AL and AC are respectively positive towards the 300° and 30° directions.

North Brazil Current

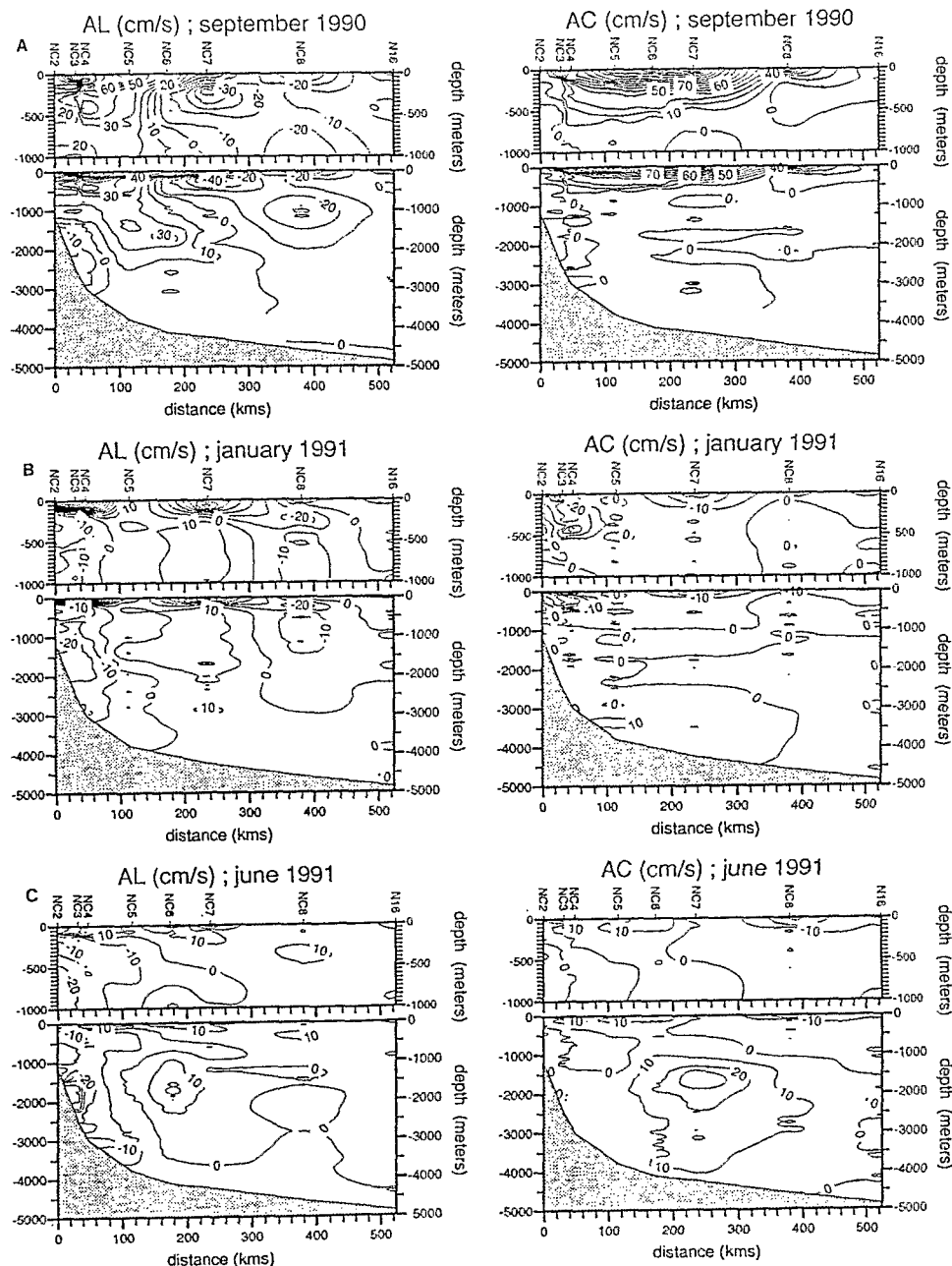
Intra-annual variability

In Ja91, representative month of the boreal winter season (Fig. 2 b and 3 b), the coastal current is strong ($120 \pm 11 \text{ cm/s}$) positive (northwestward), trapped

Figure 2

Vertical sections of the *Pegasus* alongshore (AL: left panels) and across-shore (AC: right panels) components of the velocity of the current (cm/s) along the "Cayenne" line in: a) September 1990 (S90); b) January 1991 (Ja91); and c) June 1991 (Ju91).

Sections verticales des composantes parallèle (AL : à gauche) et perpendiculaire (AC : à droite) de la vitesse du courant (cm/s) déduites des profils *Pegasus* effectués en: a) septembre 1990 (S90); b) janvier 1991 (Ja91); et c) juin 1991 (Ju91) le long de la radiale «Cayenne».



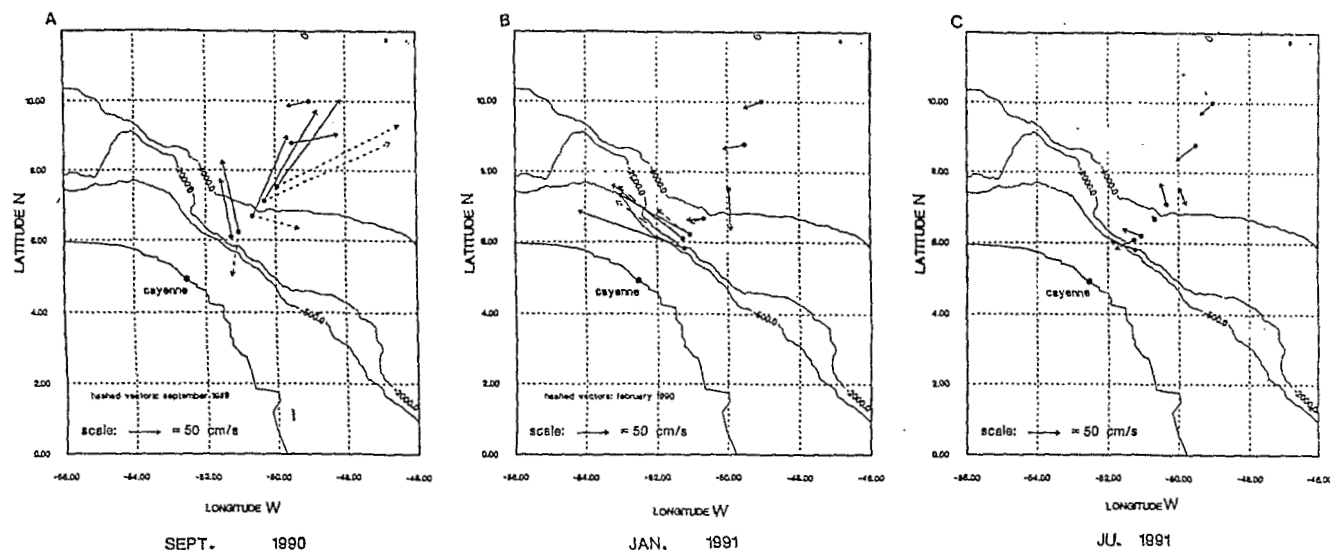


Figure 3

Surface Pegasus current vector (cm/s) referenced to the north along the "Cayenne" line in September 1990 (a), January 1991 (b) and June 1991 (c). The dashed vectors superimposed on the (a) and (b) figures respectively indicate the velocity values obtained in September 1989 and February 1990.

Distributions horizontales du vecteur courant en surface (cm/s) déduites des profils *Pegasus* effectués en septembre 1990 (a), janvier 1991 (b) et juin 1991 (c) le long de la radiale « Cayenne ». En surimpression (vecteurs en pointillés) ont été reportés sur les figures (a) et (b) les vecteurs courant obtenus respectivement en septembre 1989 et février 1990.

against the coast (within 250 km of the shelf break), confined in the first 50 metres on the shelf (figure not shown here) and 250 metres offshore. Seaward of the coastal current, a negative flow (southeastward) is observed with lower speed (-20 ± 3 cm/s). Between these two opposite flows, the across-shore current is directed towards the coast with a maximum speed of -40 ± 4 cm/s at station NC7. This period corresponds to the "cold" (Sea Surface Temperature down to 27.1°C) and "fresh" (Sea Surface Salinity < 31) seasons over the continental shelf of French Guiana (Fig. 4 a). Offshore, the waters are warmer (up to 27.8°C) and the salinity is higher (more than 36). This current pattern shows a feeding of the coastal current by offshore waters as clearly indicated by the presence of warm and saline waters along the shelf.

In S90, representative month of the summer season (Fig. 2 a and 3 a), the current system is now displaced eastward with a higher current intensity (150 ± 10 cm/s) observed. This difference of speed does not appear in the AL component which is weaker (100 ± 8 cm/s) near the shelf break but in the AC one, which is now positive and much higher (120 ± 10 cm/s) than in winter. This pattern corresponds to the NBC retroflection period as observed earlier in different current data sets. On the shelf, the Amazon fresh waters are found south and seaward of Cayenne; they are associated with a tongue of low salinity value (32), high temperature (more than 28.3°C) and eastward flows (Fig. 4 b).

Between these two current patterns described in January 1991 and September 1990, two transition periods are observed. The first, in June-July (Fig. 2 c and 3 c), corresponds to weaker AL and AC values: AL is positive (20 ± 3 cm/s) along the shelf break and decreases offshore while

extending as far as station N16 in a very thin (less than 100 m) surface layer; AC on the contrary presents opposite values: 10 ± 2 cm/s (-10 to -20 ± 3 cm/s) to the southwest (northeast) of station NC7 where a thermal front (SST difference of 0.5°) is observed there (figure not shown). The second transition period occurs in December-January: the drifter deployed at $6^\circ 30' \text{N}$ - $50^\circ 30' \text{W}$ at the end of October 1990 (courtesy of W. Brown) is motionless during the first fifteen Julian days, and then describes loops in the clockwise sense while moving northwestward. The mean speed, radius and period of the first loop are respectively: 94 cm/s, 105 km and 8 days (this period is far from the 3.73-day inertial period at 8°N); after that the periods (radius) increase (decrease) two and half months later (end of December and beginning of January), the mean speed is reduced to 11 cm/s and the trajectory becomes almost linear. At the end of Ja91, the velocity again increases up to 34 cm/s which corresponds to the onset of another boreal winter situation (Fig. 5).

Year-to-year comparison

Comparison between *Pegasus* measurements carried out at the surface first in F90 and Ja91, then in S89 and S90 reveals qualitative similarities (Fig. 2 a, 2 b and 6) but quantitative differences: in winter, the mean AL current velocity component is higher in Ja91 (137 ± 12 cm/s) than in F90 (94 ± 9 cm/s), in agreement with the Northeast pseudo surface wind stress mean anomalies observed at these times (Servain, 1990 and 1991); in summer and offshore, the AC current velocity component is higher in S90 (148 ± 10 cm/s) than in S89 (98 ± 7 cm/s), although the

Figure 4

Temperature ($^{\circ}\text{C}$) and salinity surface distributions in March 1990 (a) and October 1990 (b) off French Guiana. "m" indicates the salinity minimum associated with the coastal current retroflexion.

Distributions de la température ($^{\circ}\text{C}$) et de la salinité en surface en mars 1990 (a) et octobre 1990 (b) au large de la Guyane française. « m » indique la position du minimum de salinité associé à la réflexion du courant côtier.

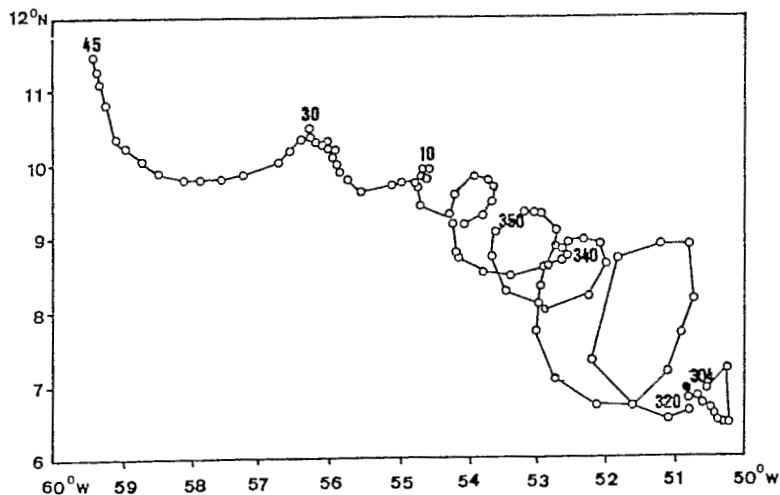
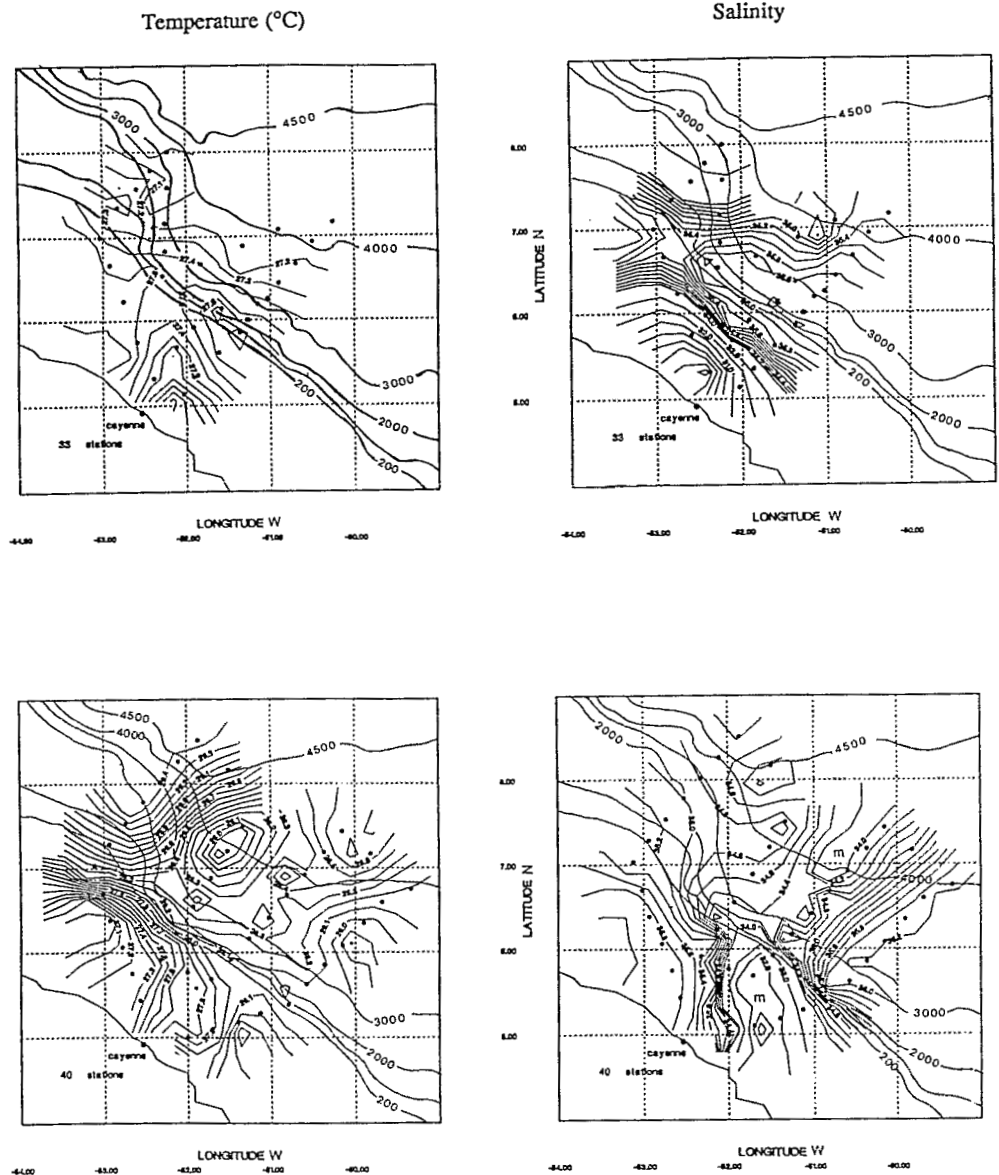


Figure 5

Drifter trajectory off French Guiana from October 1990 to February 1991 (courtesy of W. Brown). Circles are spaced at intervals of one day along the trajectory (values in Julian days).

Trajectoire de la bouée dérivante déployée au large de la Guyane française d'octobre 1990 à février 1991 (communication personnelle de W. Brown). Chaque cercle indique la position quotidienne moyenne de la bouée le long de sa trajectoire (les valeurs sont en jours juliens).

Table 2

Mass (in Sverdrups), temperature (10^{15} Watts) and salt (10^3 t/s) fluxes with the corresponding errors for the NBC, WBUC and the DWBC across the Pegasus section off Cayenne, in September 1990, January 1991 and June 1991.

Flux de masse (en Sverdrups), de température (10^{15} Watts) et de sel (10^3 t/s) et erreurs associées, à travers la section *Pegasus* située au large de Cayenne, pour le CNB, le CCBO et le CPBO en septembre 1990, janvier 1991 et juin 1991.

		SEPT. 1990 / SEPT. 1989		JAN. 1991 / FEB. 1990		JUNE 1991
NBC	Flux (Sv)	55 $\pm$ 3	81 $\pm$ 4	15 $\pm$ 1	13 $\pm$ 1	5 $\pm$ 0.2
	Temp. (PW)	66.41 $\pm$ 8.59	91.27 $\pm$ 4	18.60 $\pm$ 1.76	11.42 $\pm$ 0.96	7.12 $\pm$ 0.98
WBUC	Flux (Sv)	—	—	-5 $\pm$ 1	-3 $\pm$ 0.4	-19 $\pm$ 2
	Temp. (PW)	—	—	-6.30 $\pm$ 1.89	-3.54 $\pm$ 0.6	-21.70 $\pm$ 1.75
DWBC	Flux (Sv)	-7 $\pm$ 1	-59 $\pm$ 6	-33 $\pm$ 3	-15 $\pm$ 1	-36 $\pm$ 3
	Temps (PW)	-11.86 $\pm$ 1.46	-72.90 $\pm$ 3	-39.07 $\pm$ 3.74	-17.78 $\pm$ 2.15	-47.12 $\pm$ 3.89

veering of the NBC is more accentuated in S89 than in S90 (Fig. 3 a). S90 to Ja91 corresponds to an intense surface circulation period. These differences could be partially due to the propagation of the very energetic 40-60-day period eddies present there and which mainly influence the mean currents all over the water column (Johns *et al.*, 1990; Colin *et al.*, 1991 c and 1992 b).

Mass flux

The mean NBC mass flux (34 ± 9 Sv) deduced from the five sections is positive (northwestward), maximum in summer (68 ± 7 Sv) and minimum in winter (14 ± 2 Sv). Comparing the three S90, Ja91 and Ju91 NBC mass fluxes (Tab. 2), the flux is maximum (55 ± 3 Sv) in S90 due to both the increase of the velocity and the spatial extension (until station NC7 and down to 1 000 m depth offshore) of the NBC. In Ja91, the flux is smaller (15 ± 1 Sv) due now to a heavy trapping of the NBC against both the slope (to the southwest of station NC5) and the surface (down to 250 m depth). The minimum appears in Ju91 (5 ± 0.2 Sv) although the surface current is positive everywhere but weak and much confined to the surface (only down to 150 m depth); this situation corresponds, as mentioned earlier, to the first transition period. The mean transport obtained by Schott *et al.* (1993) from three moored stations at the western end of the equator in the Atlantic, along 44° W, is 23.8 ± 3 Sv over one year in the range 0-300 m with the maximum observed from June to September and the minimum in northern spring.

The year-to-year NBC mass fluxes comparison (F90 with Ja91 and S89 with S90) shows similar values in Ja91 (15 ± 1 Sv) and F90 (13 ± 1 Sv) but main differences between S89 (81 ± 4 Sv) and S90 (55 ± 3 Sv) despite the presence of a southeastward current close to the shelf break at the surface in 1989. These values are only instantaneous indicators and reveal the complexity of inferring an inter-annual variability for the mass flux in an area where a strong recirculation is present.

Western Boundary UnderCurrent

Intra-annual variability

The current sections off French Guiana exhibit the presence of a coastal equatorward undercurrent (hereinafter referred to as Western Boundary UnderCurrent). The S90, Ja91 and Ju91 current vertical sections and profiles (Fig. 2 and 6) show, in Ja91, a current, trapped (within 100 km) against the continental slope, associated with a velocity of -23 ± 3 cm/s at 330 m depth and a depth extension down to 750 m depth; in Ju91 the current is wider (more than 200 km off the shelf break) with a larger vertical extension (down to more than 1 000 m depth) and speed (-29 ± 2 cm/s at 730 m depth). The WBUC is absent in S90 at the latitude of Cayenne but present north of French Guiana ($8^\circ 30'$ N) both in the *Pegasus* (-10 ± 2 cm/s between 100 and 600 m depth, courtesy of K. Leaman) and mooring data (Johns *et al.*, 1990). The signature of a such subsurface southeastward flow also appears in February 1990, in a NOE temperature AC section located off Cayenne (Fig. 7), which clearly indicates a deepening of the isotherms towards the coast in that depth range. Molinari and Johns (1992) suggest, from climatological salinity distributions, a Caribbean Sea origin for this undercurrent. The Community Model Effort (CME) simulations of the monthly mean zonal and meridional components of the currents along 53° W also show the presence of a southeastward flow at the same months and level (F.A. Schott, personal communication).

Year-to-year comparison

The current measurements from 1989 to 1991 exhibit time and space variabilities at that level: vertical extension and intensity of the WBUC are respectively weaker and higher in F90 (-33 ± 3 cm/s) than in Ja91 (Fig. 6). Further current measurements are obviously needed at that level in order better to describe the variability of the WBUC at that time scale.

Figure 6

Alongshore (AL in cm/s) Pegasus vertical profiles component (0-3 000 m) at stations NC2 to NC5 in January 1991 (left), June 1991 (middle) and September 1990 (right) at the top and in February 1990 (left) and September 1989 (right) at the bottom.

Profils verticaux Pegasus (0-3 000 m) de la composante de la vitesse du courant parallèle à la côte (AL en cm/s) obtenus aux stations NC2 à NC5 en janvier 1991 (gauche), juin 1991 (centre) et septembre 1990 (droite) en haut et en février 1990 (gauche) et septembre 1989 (droite) en bas.

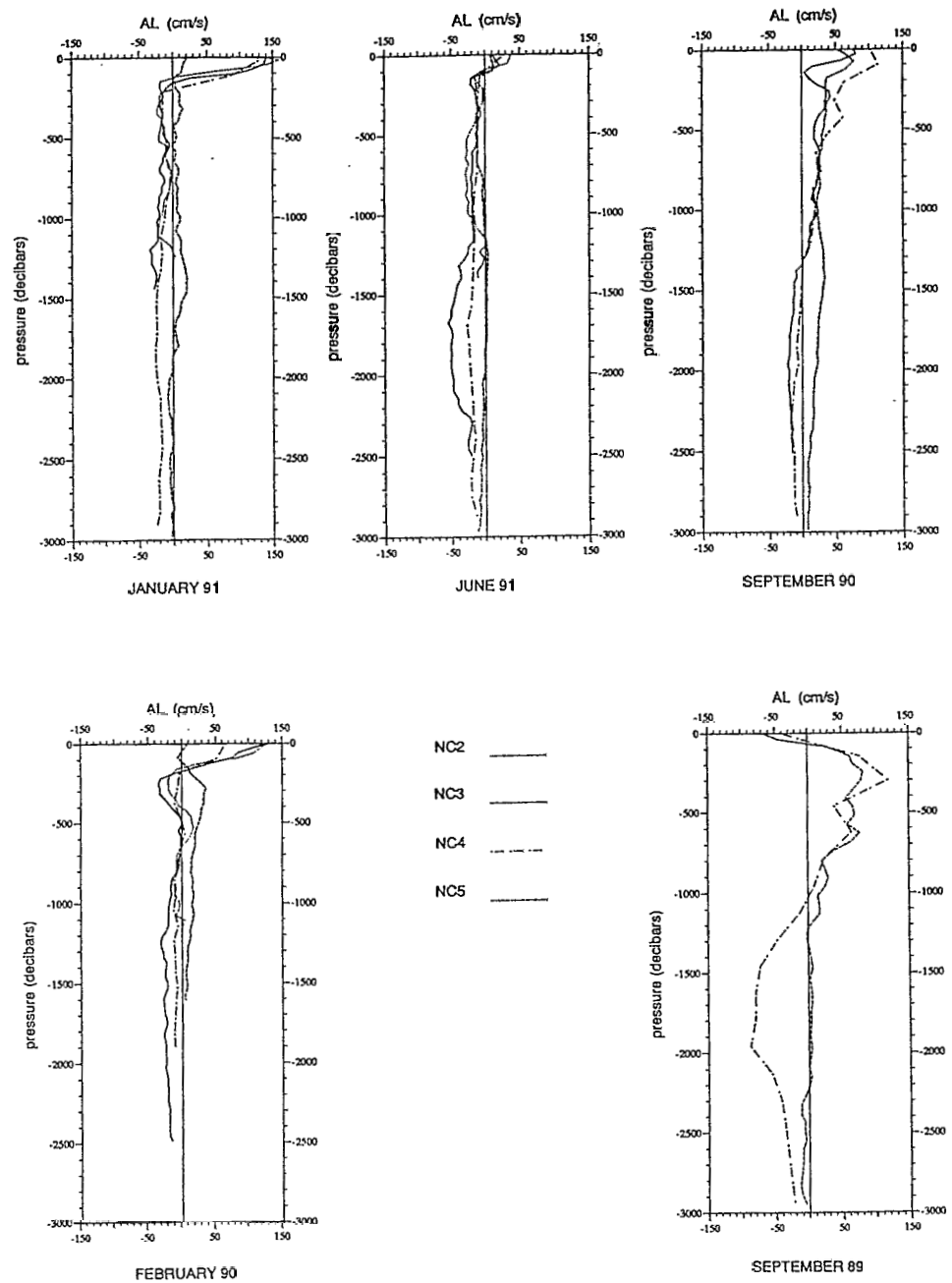


Table 3

Integrated mass (IMF in Sverdrups), temperature (ITF; 10^{15} Watts) and salt (ISF; 10^3 t/s) fluxes with the cumulated errors in September 1990, January 1991 and June 1991 with the mean. The evaluations concern the section NC2-N16 and 0-3 000 m depth. The 0-5 000 m IMF, ITF and ISF computed in January 1991 and June 1991 are between parentheses.

Flux intégrés de masse (IMF en Sverdrups), de température (ITF en 10^{15} Watts) et de sel (ISF en 10^3 t/s) et erreurs cumulées associées, en septembre 1990, janvier 1991 et juin 1991, ainsi qu'en moyenne sur les trois périodes. Les évaluations concernent la section NC2-N16 entre 0 et 1 000 m de profondeur. Les IMF, ITF et ISF calculés pour janvier 1991 et juin 1991 entre 0 et 5 000 m sont indiqués entre parenthèses.

	SEPT. 1990	JAN. 1991	JUNE 1991	MEAN
IMF (Sv)	1.88 ±19.20	-13.29 ±17.04 (-0.72 ±19.77)	-3.79 ±10.14 (-9.96 ±11.86)	-5.07 ±46.38
ITF (PW)	3.09 ±30.08	-15.62 ±26.49 (-0.47 ±30.40)	-3.99 ±16.32 (-11.42 ±19.19)	-5.51 ±72.89
ISF (Tt/s)	74.22 ±1845.48	-477.82 ±1593.62 (-19.12 ±1832.32)	-129.64 ±988.63 (-355.32 ±1164.72)	-177.75 ±4427.73

Mass flux

The WBUC mass fluxes computed for the S90, Ja91 and Ju91 sections (Tab. 2) lead to a maximum value in Ju91 (-19 ± 2 Sv from 130 down to 1 100 m depth and to the southwest of station NC6) and a minimum one in Ja91 (-5 ± 1 Sv from 150 down to 600 m depth and to the southwest of station NC5). The comparison between the two winter sections shows an absolute velocity maximum higher in F90 than in Ja91, but a WBUC mass flux stronger in Ja91 than in F90 (-3 ± 0.4 Sv), due to a higher vertical extension of the WBUC in Ja91. The moored current measurements obtained by Schott *et al.* (1993) in the equatorial band along 44°W give, on the contrary, a mean northwestward transport of 6.7 Sv in the range 300-600 m, indicating in winter-spring the retroflexion of the deeper part of the NBC between the equator and 5°N as observed in December 1982 by Flagg *et al.* (1986).

Deep Western Boundary Current

Intra-annual variability

The Deep Western Boundary Current has first been inferred at $26^\circ 30' \text{N}$ from geostrophy and tracer distribution (Fine and Molinari, 1988) and then observed from moored current measurements (Lee *et al.*, 1990). Off French Guiana, on the three S90, Ja91 and Ju91 current vertical sections and profiles (Fig. 2 and 6), the DWBC is trapped against the continental shelf break within a distance averaging less than 100 km and located in the depth layer 1 200-3 000 m. This southeastward flow is moreover associated with the high salinity values (34.9-35.00) of the upper part of the North Atlantic Deep Water. The maximum velocity (-50 ± 3 cm/s) is observed in June (1991) in the depth range 1 700-1 900 m and the minimum (-23 ± 2 cm/s) in September (1990), slightly deeper (1 900-2 000 m); this minimum is related to both the deep extension and the velocity increase of the NBC at that time. Seaward of the DWBC, a sequence of northwestward and southeastward flows emphasizes the presence of a strong horizontal recirculation at that level. Richardson *et al.* (1993 *a*) observed from neutrally buoyant SOFAR floats tracked at 1 800 m depth for 21 months, the presence of a swift (> -50 cm/s), narrow (100 km wide) DWBC extending from 7°N to the equator. Schott *et al.* (1993) also observed, now from moored current measurements over two yearlong deployments at the equator and at 44°W , a current core with maximum annual southeastward speed of -30 cm/s along the slope and in the range 1 400-3 100 m. It is noteworthy that the horizontal current distribution simulated at 2 125 m by the Community Modelling Effort numerical model (courtesy of F.A. Schott) shows, in spring and fall, a DWBC trapped against the shelf break at the latitude of Cayenne.

Year-to-year comparison

The vertical *Pegasus* profiles obtained in winter (F90 and Ja91) and summer (S89 and S90) exhibit quantitative differences :

in winter (Fig. 6), the DWBC is faster (-33 ± 2 cm/s) and wider in 1991 than in 1990 (-23 ± 2 cm/s); in summer, the DWBC is slower (maximum speed -23 ± 2 cm/s) and narrower (seaward limit between stations NC4 and NC5) in 1990 than in 1989 (respectively -92 ± 6 cm/s and to the west of station NC5). This large southeastward flow along the slope in S89 is also associated offshore with important northwestward flows (respectively 26 ± 3 cm/s and 21 ± 3 cm/s at stations NC6 and NC7), suggesting at that time and at that level a strong horizontal recirculation. There are no reasons to suspect, from the data available, the high velocity values observed in S89 at that level : they might be due for a part to a superimposition of a southeastward flow, associated with the anticyclonic 40-60-day period eddy propagation, on the mean currents (Johns *et al.*, 1990).

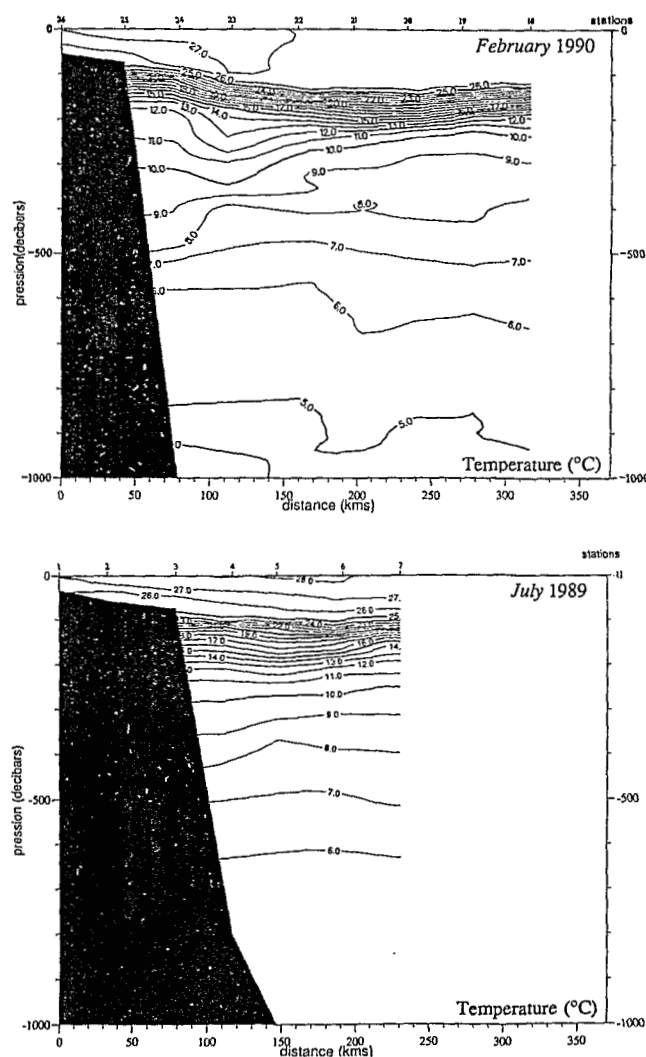


Figure 7

Temperature ($^{\circ}\text{C}$) vertical section (0-1 000 m) off French Guiana in February 1990 and July 1989, starting at a distance of 90 km off the coast.

Coupe verticale (0-1 000 m) de la température ($^{\circ}\text{C}$) au large de la Guyane française en février 1990 et juillet 1989, à partir d'une distance de 90 km de la côte.

Mass flux

The mean DWBC mass flux computed over all the vertical sections down to 3 000 m depth is -30 ± 14 Sv. Considering the three S90, Ja91 and Ju91 periods, the DWBC mass fluxes indicate a large intra-seasonal variability: maximum in Ja91 and Ju91 (respectively -33 ± 3 Sv and -36 ± 3 Sv) and minimum in S90 [-7 ± 1 Sv (Tab. 2)]. The weakness of the DWBC flux in S90 is due to the very deep extension of the surface northwestward flow, trapped against the continental slope at that time. The year-to-year comparison indicates smaller fluxes in F90 (-15 ± 1 Sv) and S90 than in Ja91 and S89 (-59 ± 6 Sv); the summer mean (-33 ± 7 Sv) is larger than the winter one (-24 ± 4 Sv) due to the weight of the S89 DWBC value. These values have to be compared to the mean following ones: 22 Sv (8°N , 52°W) obtained by Johns *et al.* (1993) from a yearlong deep mooring in the range 2 500 m-bottom, 15 Sv (between 7°N and the equator) by Richardson *et al.* (1993) from SOFAR floats displacements in the range 900-2 000 m and 22 Sv (equator, 44°W) by Schott *et al.* (1993) from three moored stations in the range 1 400-4 200 m (mean depth of the 1.8°C isotherm).

Very deep flow

The presence of a bottom-intensified southeastward current has been reported off the southern Bahamas and Barbuda at many STACS cruises (R.L. Molinari, personal communication) and is identified as the Lower North Atlantic Deep Water core; this current also appears in the one-year record duration of the mooring current measurements, north of French Guiana, at 3 840 m (-20 ± 12 cm/s) and 4 340 m (-28 ± 14 cm/s) depths with larger mean values in winter than in summer (Johns *et al.*, 1990). Off

Cayenne, at a similar distance from the coast (station NC7) and below 3 500 m depth, the AL *Pegasus* velocity components (Fig. 8) are weak and erratic: southeastward (-3.5 ± 1 cm/s) in Ju91 but northwestward in Ja91 (3 ± 1 cm/s) and S89 (9.5 ± 2 cm/s); all the AC vertical profiles however exhibit at these locations and levels the permanence (Fig. 2, right panels) of a positive (northeastward) component; the absolute maximum (12 cm/s) is observed in Ju91 at 4 000 m depth. The deeper part of this flow (Fig. 8), up to station NC8, follows the bottom topography. In any case, the *Pegasus* profiles off Cayenne never exhibited as clearly as on the moored current records obtained further north by Johns *et al.* (1993) at the base of the slope a southeastward velocity (~ 35 cm/s core speed, 60 km width) in the depth band 3 700-4 500 m. Seaward, below 4 650 m and at station N16, AL is now positive (7 ± 2 cm/s) both in S90 and Ja91 (Fig. 9) while AC is permanently negative indicating there the presence of a northwestward Very deep Flow; this bottom flow is associated with the low (lower than 34.90) AntArctic Deep Water salinity minimum (Fig. 9).

Mean Currents and associated Standard Deviations

The mean AL and AC current velocity components and respective standard deviations have only been computed over the three S90, Ja91 and Ju91 complete sections (Fig. 10). The mean AL vertical section clearly exhibits the presence of the two main currents to the southwest of station NC5: the NBC with a mean intensity of 80 cm/s trapped along the shelf break and associated with a mean standard deviation of 35 cm/s, and the DWBC with a mean velocity core of -25 cm/s centered in the depth band 1 300-2 200 m and associated with a mean standard deviation of 5 cm/s. The

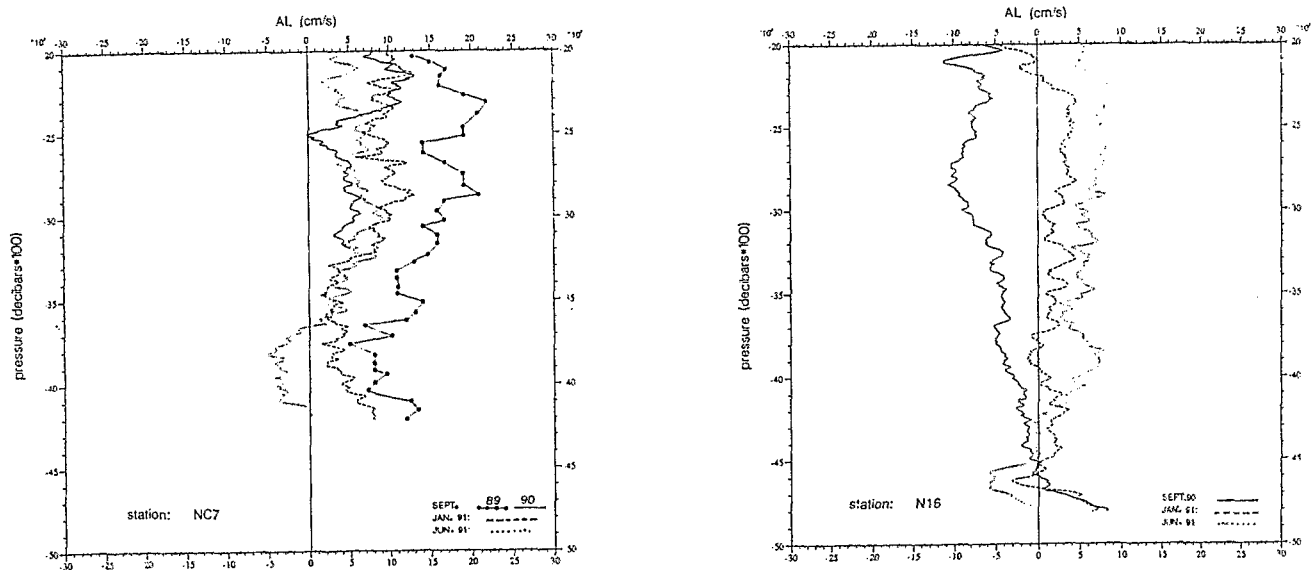


Figure 8

Alongshore (AL) *Pegasus* vertical (2 000-5 000 m) profiles component (cm/s) of the current velocity at station NC7 (left) and station N16 (right) in September 1990 (full line), January 1991 (dashed line) and June 1991 (light dotted line). The September 1989 profile has been superimposed (heavy dotted line) at station NC7.

Profils verticaux *Pegasus* (2 000-5 000 m) de la composante (cm/s) de la vitesse du courant parallèle à la côte (AL) obtenus aux stations NC7 (gauche) et N16 (droite) en septembre 1990 (continu), janvier 1991 (tirés) et juin 1991 (pointillés). Le profil vertical obtenu en septembre 1989 (continu gras) à la station NC7 a été superposé.

Salinity (STACS, january 1991)

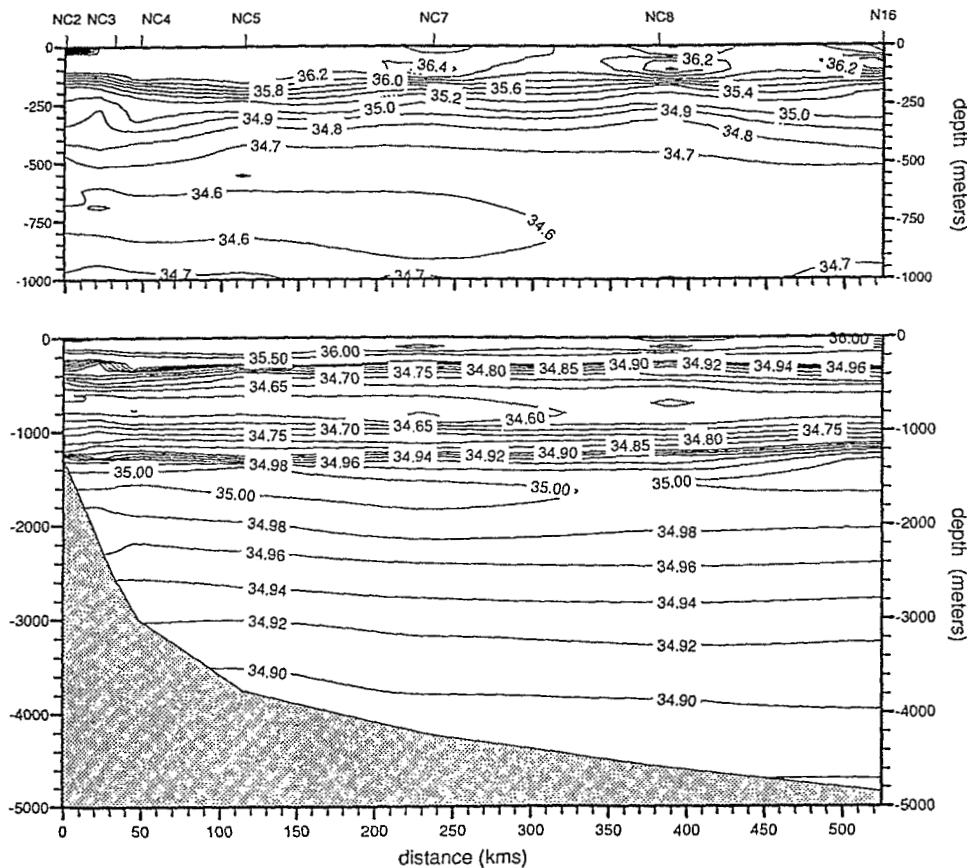


Figure 9

Salinity vertical section along the "Cayenne" line in January 1991.

Coupe verticale de la salinité le long de la radiale « Cayenne » en janvier 1991.

WBUC does not appear on this figure, but the associated standard deviation is high (up to 20 cm/s) at that level. At the DWBC level, AL is positive between stations NC5 and NC7 and negative again beyond NC7, suggesting there a strong recirculation. The mean AC component is positive and weak everywhere except at the surface between stations NC4 and NC7, where a maximum value (35 cm/s) is observed, centred at station NC5; the associated standard deviation is large and a value of up to 45 cm/s is obtained at station NC7.

The mean NBC and DWBC mass fluxes, computed over these three complete sections, are not in balance respectively (25 ± 4 Sv and -33 ± 9 Sv), indicating the importance of the DWBC and the associated NADW (upper part) in the coastal oceanic circulation at the latitude of Cayenne.

INTEGRATED FLUXES

Two Integrated Fluxes (Tab. 3) have been computed across the whole section (NC2 to N16): the first from the surface down to 3 000 m depth, and the second (in Ja91 and Ju91 only) from the surface down to the bottom (values are between parenthesis in that case).

Mass flux

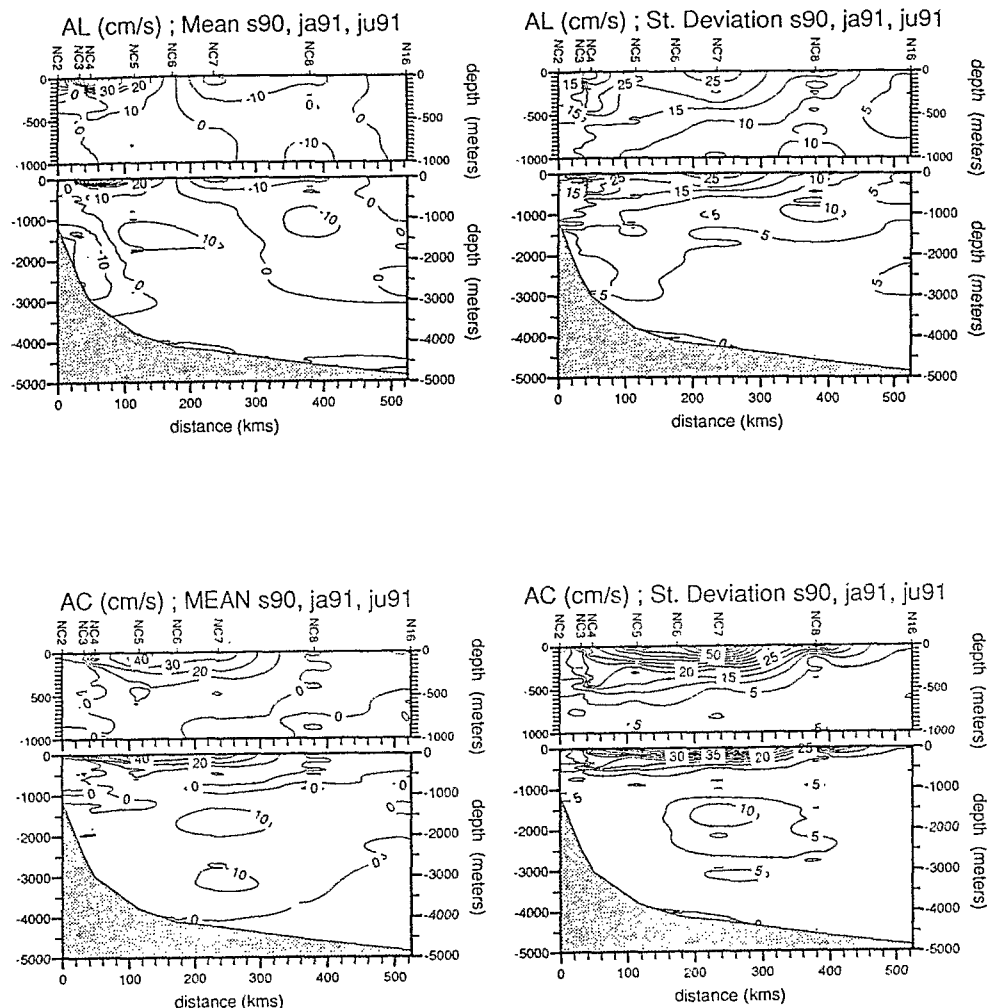
The Integrated Mass Flux (IMF) in S90, Ja91 and Ju91 are, with the cumulated errors, respectively to: 1.9 ± 19.2 Sv, -13.3 ± 17.0 Sv (-0.7 ± 19.8 Sv) and -3.8 ± 10.1 Sv (-9.9 ± 11.9 Sv), indicating the presence of a clear season-

nal cycle off French Guiana. The differences observed between the mass fluxes computed for the two layers: surface-3 000 m and surface-bottom, indicate that in Ja91 (Ju91) the transport evaluation is influenced by the offshore northwestward (southeastward) flow (Fig. 2) observed at station N16 (base of the slope). The mean IMF (0-3 000 m) is weak but negative (-5.1 ± 46.4 Sv), showing the importance of the southeastward flows (WBUC and DWBC) in the area. If the computation in the layer 0-3 000 m is now limited to the horizontal extension of the DWBC (within 100 km of the shelf break), the mean IMF is still of the same order of magnitude (-5 ± 8 Sv) which is much less than the mean value obtained by Lee *et al.* (1990) at $26^{\circ}30$ N (-30 Sv down to 4 800 m depth) from mean moored current measurements. This difference does not concern the mean DWBC transport (-33 Sv in Lee's case and -30 ± 14 Sv in our case despite different upper and lower integration limits: respectively, 800 m-bottom and 1 000-3 000 m) but mainly the upper layer transports: 3 Sv in Lee's (above 800 m) and 25 ± 9 Sv (0-1 000 m in mean) in our case. If the comparison is extended further south to the moored current measurements carried out at 44° W in the equatorial band (Schott *et al.*, 1993), a mean IMF of 15 Sv (computed over two consecutive yearlong deployments) is obtained, shared out in 31 Sv from the surface down to 600 m depth and only -16 Sv in the range 1 400-3 100 m depth. In conclusion, the data indicate a substantial decrease of the NBC (DWBC) mass flux, particularly north (south) of Cayenne.

Figure 10

Vertical sections of the average Pegasus alongshore (AL: top panels) and average Pegasus across-shore (AC: bottom panels) velocity components of the current (cm/s) (left panels) and respective standard deviations (right panels). The averages and standard deviations are computed from the September 1990, January 1991 and June 1991 periods.

Sections verticales de la composante parallèle à la côte moyenne (AL: en haut) et de la composante perpendiculaire à la côte moyenne (AC: à droite) de la vitesse du courant (cm/s) (à gauche) et des écart-types associés (à droite). Les moyennes et écart-types sont calculés à partir des profils Pegasus effectués en septembre 1990, janvier 1991 et juin 1991.



Temperature flux

The Integrated Temperature Flux (ITF), computed in the same manner as the IMF, is positive in September and negative in January and June 1991: respectively, 3.1 ± 30.1 PW in S90, -15.6 ± 26.5 PW (-0.5 ± 30.4 PW) in Ja91 and -4.0 ± 16.3 PW (-11.4 ± 19.2 PW) in Ju91. The mean ITF is -5.2 ± 73 PW and of the same sign as the IMF one.

Salt flux

The Integrated Salt Fluxes (ISF) amount respectively to 74 ± 1845 Tt/s in S90, -478 ± 1594 Tt/s (-19 ± 1832 Tt/s) in Ja91 and -130 ± 989 Tt/s (-355 ± 1165 Tt/s) in Ju91. The mean ISF is large and also negative (-178 ± 4428 Tt/s), indicating a southeastward salt transport tendency, mainly due to the DWBC and the associated NADW salinity maximum.

DISCUSSION

The error values mentioned above do not include those which are related first to both the interpolation and extrapolation procedures and secondly to the temporal and spatial variabilities linked to the propagation of eddies.

Interpolation and extrapolation errors

Considering the bottom topography and the velocity values observed at that level, neglect of the transports in the bottom triangles between stations pairs leads to an underestimation of these transports. However, as there are no observed intensified currents or strong velocity gradients at the bottom of the slope off French Guiana, the errors committed must remain small and in all cases less than the ± 3 Sv found by Johns *et al.* (1993) in the presence of a very deep swift flow. The errors due now of taking account of station NC2 in September 1990 is assumed at the maximum to be equal to the transport value between NC2 and NC3. The sum of all the errors would yield to the following values: for the NBC to ± 10 Sv in September 1990 (extrapolation to station NC2), for the DWBC (3 000 m-bottom) to ± 4 Sv in S90, ± 6 Sv in Ja91 and ± 12 Sv in Ju91. The error values rarely exceed 30 % of the individual transport ones, while the errors due to the measurements and the numerical processing do not exceed 20 % of the observed values.

Eddy propagation

The uncertainty in the temporal and spatial resolutions of the transports is more difficult to determine, due to the

weak number of available sections. However an estimation of this contribution can be made considering moored current meter records (twenty months) obtained in the vicinity of the NC3 *Pegasus* station from March 1990 to September 1991 at 275, 500 and 2 700 m depths (Colin, personal communication). Multiplying the mean turbulent velocity due to eddies (deduced from the turbulent kinetic energy values obtained at the three levels above respectively 400, 200 and 40 cm^2/s^2) by the mean vertical and horizontal extensions of the main currents (respectively 200 m and 250 km for the NBC, for example), yields to maximum eddy transport values of 2.5 Sv for the NBC, 0.5 Sv for the WBUC and 0.4 Sv for the DWBC. These values are of the same order of magnitude as those obtained from other colleagues in the same area, either from moored current measurements: 1 Sv by Johns *et al.* (1993) in the range 0-200 m, 2 Sv by Schott *et al.* (1993) in the range 0-500 m, or from SOFAR floats displacements: 2.7 Sv in mean by Richardson *et al.* (1993 b) in the range 0-1 000 m.

SUMMARY AND CONCLUSIONS

Pegasus current profiles carried out off Cayenne during the STACS cruises from September 1989 to June 1991 provide some information concerning the circulation and its variability along the part of the northwestern equatorial Atlantic Ocean boundary located off Cayenne. At the surface, the strong seasonal variability of the North Brazil Current has been confirmed. In winter the NBC is trapped along the coast, confined in the upper 250 metres with a velocity value of around 120 cm/s. In summer, the NBC moves and veers offshore through an anticyclonic gyre; at that time the NBC velocity increases (up to 150 cm/s) as the lower limit of the current (down to 1 000 m). The mean NBC mass flux computed for the five sections is 34 ± 9 Sv with absolute maximum and minimum respectively in September 1989 (81 ± 4 Sv) and June 1991 (5 ± 0.2 Sv). Below, the Western Boundary UnderCurrent flows in the opposite direction; the absolute velocity maximum of this southeastward flow is observed in winter (~ 29 cm/s in February 1990); in summer the WBUC is absent. The mean WBUC mass flux computed for the winter and spring sections is -9 ± 3.4 Sv. Deeper, below 1 200 m depth, the Deep Western Boundary Current is present, coastally trapped (within 100 km of the shelfbreak) with a velocity core centred in the depth range 1 700-2 000 m; the maximum (minimum) vertical extension of the DWBC appears in June 1991 (September 1990) and is associated with a maximum

(minimum) speed of ~ 50 cm/s (~ 23 cm/s). The absolute maximum has been observed in September 1989 (~ 92 cm/s), suggesting the presence of an interannual variability even at that level. The mean DWBC mass flux is -30 ± 14 Sv with absolute maximum and minimum respectively in September 1989 (-59 ± 6 Sv) and September 1990 (-7 ± 1 Sv). Below 3 800 m depth, there are some indications at the farthest station (N16) of a northwestward Very Deep Flow, particularly developed in September 1990 and January 1991 and associated with the AntArctic Deep Water low salinity values. At all depths, the vertical sections indicate the presence of a strong horizontal recirculation.

The Integrated Mass Flux computed on the whole section and down to 3 000 m depth for the September 1990, January 1991 and June 1991 sections indicate the presence of a clear seasonal cycle. The mean IMF (~ 5 Sv), although weak, is negative, reflecting the predominance of the southeastward flows off French Guiana. The mean IMF limited to the lateral extension of the DWBC is also negative and larger (~ 12 Sv), enhancing the weight of the DWBC in the area. The Integrated Temperature Fluxes is positive in September 1990 (3.1 PW) but negative both in January 1991 (-15.6 PW) and June 1991 (-4 PW). The mean ITF (~ 5.5 PW) is negative as the IMF one. The mean Integrated Salt Flux is large and also negative, indicating the importance of the upper part of the NADW (and the associated high salinity values) in the thermohaline boundary circulation.

Acknowledgements

We thank R.L. Molinari and K. Leaman (University of Miami) for their efficient support in carrying out the *Pegasus* measurements off French Guiana during the STACS cruises and F.A. Schott for providing the CME current simulations in the domain. We are also most grateful to M. Bushnell (NOAA/AOML Miami), R. Jones and P. Vertès (University of Miami), P.-Y. Noyer and J.-M. Bore from ORSTOM/Cayenne for their skilful help in obtaining and processing the *Pegasus* data. We express gratitude to the officers and crew of the NOAA vessels Mount Mitchell and Malcolm Baldrige for their assistance in the *Pegasus* operations, the *Direction Générale* of ORSTOM and the french Ministry of Overseas Departments and Territories for providing the necessary funds for the field operations. This programme is part of the USA/French Scientific Cooperation (11th Joint Session, December 1989).

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synthèse-review

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Global oceanic and atmospheric oxygen stability considered in relation to the carbon cycle and to different time scales.

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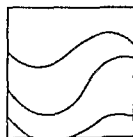
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La revue *Oceanologica Acta* est une publication de Gauthier-Villars, société anonyme, constituée pour 99 ans, au capital de 3 089 600 F. Siège social : 17, rue Rémy Dumoncel, 75014 Paris - P.D.G. : J. Lissarrague. Actionnaire : Bordas S.A. (99,8 % des parts). Direction de la publication : J. Lissarrague. Responsable de la Rédaction : J. Boutler.

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Dépôt légal 1994 Imprimeur 4024 — Éditeur 038 — CPPP 60171

Imprimé en France
Le Directeur de la publication Jean LISSARRAGUE