On steady state intermediate vertical currents induced by the Mozambique current

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RÉSUMÉ

DES COURANTS VERTICAUX STATIONNAIRES INDUITS PAR LE COURANT DE MOZAMBIQUE DANS LA COUCHE INTERMÉDIAIRE

Les recherches menées en février 1980 dans la partie septentrionale du Courant de Mozambique (10°30'-16° S) à bord du R/V « A.v. Humboldt », conjointement par la République Démocratique Allemande et la République Populaire de Mozambique, montrent que l'effet de la rotation de la terre sur les vitesses ascensionnelles au niveau intermédiaire d'un courant côtier à l'ouest d'un océan, peut être du même ordre de grandeur que l'effet cyclonique du vent sur les upwellings des courants côtiers orientaux.

Les données présentées, relatives à une région peu étudiée, indiquent l'influence de tels processus dynamiques sur la distribution des sels nutritifs dans la couche euphotique.

MOTS-CLÉS : Courant côtier — Courant géostrophique — Courant subsuperficiel — Upwelling — Canal Mozambique — Océan Indien.

ABSTRACT

Investigations carried out aboard the r/v "A. v. Humboldt", jointly between marine scientific institutions of the German Democratic Republic and the Peoples Republic of Mozambique, in the northern part of the Mozambique Current (10°30'-16° S) in February 1980 demonstrate, that the effect of the planetary vorticity on intermediate vertical velocities can be of the same order of magnitude in a western boundary current as the effect of the wind stress vorticity on upwellings in eastern boundary currents.

The presented facts from a less investigated area indicate the influence of such dynamic processes on the micro-nutrient distribution in the euphotic layer.

KEY WORDS : Coastal currents — Geostrophic currents — Subsurface currents — Upwelling — Mozambique current — Indian ocean.

1. INTRODUCTION

Western boundary currents are relatively strong and narrow currents, carrying tropical water from low to higher latitudes along the eastern coasts of the continents.

In the South Indian Ocean, along the East African coast, the poleward flowing continuation of the South Equatorial Current is represented firstly by the Mozambique Current (MC), and further south by the Agulhas Current. In contrary to the Gulf Stream, a typical western boundary current in the North Atlantic well studied during past decades, hitherto investigations of the MC had been very limited. Though intensive studies had been carried out during the International Indian Ocean Expedition, dynamic features of this region were investigated only incompletely, WYRTKI (1971).

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First results related to the distribution of the mass and pressure fields in the Mozambique Channel were published by MENACHE (1963). However, this paper does not refer to details of the specific dynamics of the MC. Until now the dynamics of this current are only poorly understood, and additional investigations are required in this region.

While the conditions in the southern entrance to the Mozambique Channel are better known particulary in relation to the transport processes from the MC into the Agulhas Current, LUTJEHARMS, BANG and DUNCAN (1981), knowledge on the middle and northern part of this current is still very limited.

During a survey of the fishery resources of the waters adjacent to Mozambique, SAETRE and SILVA (1979) carried out oceanographical investigations off the coast of Mozambique in 1977/78. On the basis of their observations the authors concluded, that along the coast off Mozambique, between about 10°30′ S and 16° S, coastal upwelling occurs inside of a narrow zone of about 30 to 50 km width. Unique from other western boundary currents, the northern part of the Mozambique Channel is characterized by a strictly meridional orientated coast line. Therefore it is possible to determine the order of vertical currents produced by the effect of the planetary vorticity on the southward flowing MC and on its countercurrents. Moreover, it can be expected, that the vertical currents induced in such a way show distinct relations with regard to the micro-nutrient distribution in the euphotic layer.

2. DATA

The oceanographical investigations were performed on board the r/v "A. v. Humboldt" of the Academy of Sciences of the German Democratic Republic, according to an agreement between the Institut für Meereskunde, Rostock-Warnemünde, and the Instituto de Desenvolvimento Pesqueiro, Maputo.

Fig. 1 shows an overview of measurements and observations carried out during the expedition. The oceanographical data of this paper come from the sea area between 10°30′ and 16° S, and were obtained during the period of 20 to 28 February 1980. For measuring temperature, salinity, pressure and other interesting parameters a bathysonde type instrument "OM-75" was employed, MÖCKEL (1980), designed by the Institut für Meereskunde Rostock-Warnemünde.

Data corrections and validation were made, according to standard procedures, for every water layer with a thickness of 2,5 meters. The mean standard deviation of the sensor data compared to thermometer measurements amounted to $\overline{\Delta T} = \pm 1{,}3 \cdot 10^{-2}$ °C, the deviation of the sensor data in comparison with the salinometer determinations to $\overline{\Delta S} = \pm 1{,}9 \cdot 10^{-2}$ ‰. Furthermore, the salinity is computed from the temperature, conductivity and pressure according to the old standard formula.

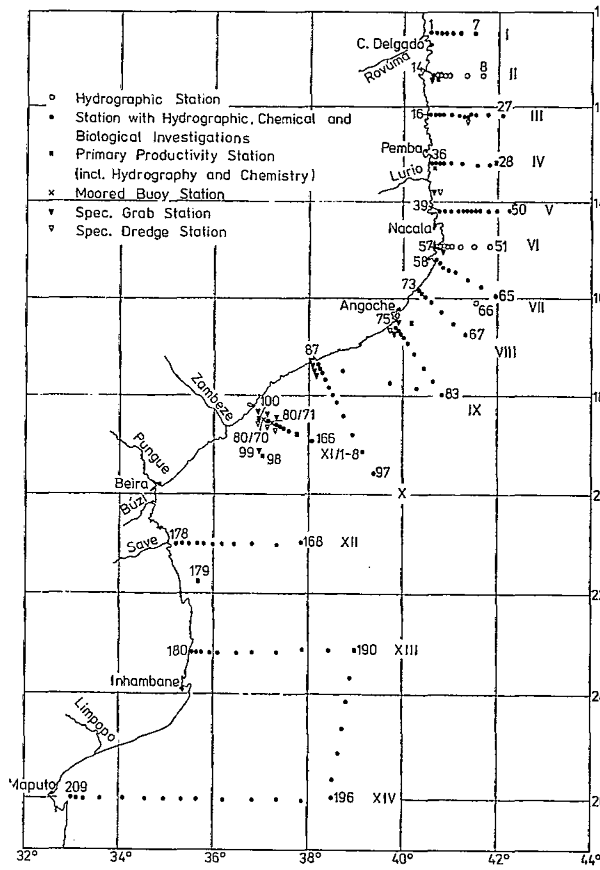

FIG. 1. — Station grid of "A. v. Humboldt" during 20. February to 30. March 1980.

Carte des stations effectuées par le "A. v. Humboldt" du 20 février au 30 mars 1980.

3. COMPUTATION OF THE STEADY STATE VERTICAL VELOCITIES

The calculation of the current velocity by the measurement of horizontal and vertical density structure received new attention from the beta spiral method by STOMMEL and SCHOTT (1977), as well as from the inverse method by WUNSCH (1978). A comparison of the two methods was made by KILLWORTH (1980), who solved the problem of the indirect velocity estimation from oceanographical data sets on the basis of a natural zero level of currents below the level of Ekman-pumping produced by the windstress vorticity. The precondition for that is the existence of an intermediate layer of no motion.

In the Mozambique Channel, the vertical density profiles by MENACHE (1963) don't indicate the disappearance of the horizontal density gradients down to a depth of 600 m. The lower most measuring depth of the R/V "A. v. Humboldt" was the 600 dbar surface. Therefore, this level was arbitrarily assumed to be a layer of no essential motion.

A right-handed cartesian coordinate system is commonly used with the x-axis aligned zonal to East, the y-axis aligned alongshore to North, the z-axis vertical upwards. Corresponding current components are (u, v, w). The pressure is $p = p(x, y, z)$, and the density $\rho = \rho(x, y, z)$, respectively. The reference level is 600 dbar. The general boundary conditions are also shown in fig. 2. The Coriolis parameter $f = 2\vec{\omega} \sin \varphi$ takes into account the angular veocity of earth's rotation $\vec{\omega}$ in the geographic latitude φ.

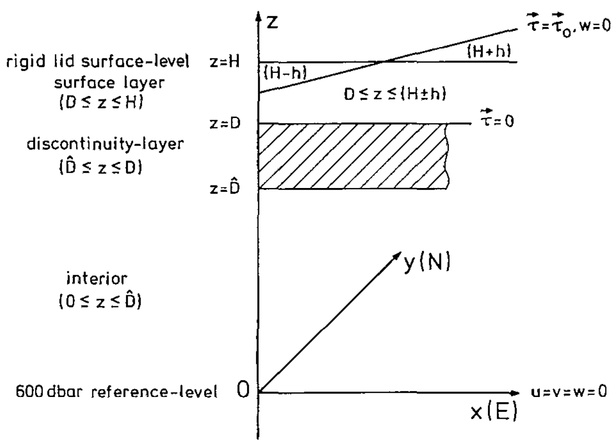

FIG. 2. — Used coordinate system and boundary conditions with $\hat{D} \approx D$.

Système de coordonnées employé et situation côtière avec $\hat{D} \approx D$.

All these considerations are referred to an intermediate water column $0 < z < D$, in which the effects of the wind stress disappears. On the understanding that the flow is geostrophic, we may write the equations of motion in the geostrophic component form:

$$(1.1.)\quad -vf + \rho^{-1}.P_x = 0$$
$$(1.2.)\quad uf + \rho^{-1}.P_y = 0$$
$$(1.3.)\quad g + \rho^{-1}.P_z = 0$$

In the expression (1.3.) g is the acceleration of gravity. The partial derivations are described by $(\ )_{x,y,z}$. One obtains with the aid of the continuity equation, neglecting the diffusions, the vortex stretching equation of KILLWORTH (1980) by the partial derivation of (1.1.) with respect to y, and (1.2.) with respect to x, and by subsequent subtraction:

$$(2.)\quad (\rho w)_z = (\rho v)\beta/f = p_x\beta/f^2 \qquad \text{with } f < 0.$$

In this formula $\beta = f_y$ and $f \neq 0$. Expression (2.) states, that the planetary vorticity makes a contribution to the vertical steady state velocity and to the zonal pressure gradient.

Except for the absence of the share of the wind stress vorticity, equation (2.) corresponds to the formula given firstly by YOSHIDA and MAO (1957). These authors proved, that coastal upwelling processes along the coast of California are primarily caused by the wind stress vorticity. In case of a disappearing zonal pressure gradient within the reference level, with the aid of equation (2) the geostrophic portion of the w-component can be determined relative to this reference surface.

If, according to formula (2) $\int_0^D (\rho v)dz < 0$, then $(\mathscr{L}w)_{z=D} > 0$. That means, that the integral southward transport produces ascending water movements in the level $z = D$. This fact is commonly expressed by an upward motion of the pycnocline. On the other hand a corresponding northward flowing countercurrent induces descending water motions at the same surface. This statement elucidates the general consequence of the space-temporal shifting of the core of MC during the year relative to the temporal and spatial intensity of $(\rho w)_{z=D}$.

The following estimations of the integrated geostrophic velocity $w_{z=D}$ were computed on the basis of the geostrophic meridional velocity by (1.1.) according to (2). The accuracy of dynamic computations is discussed in the appendix.

4. RESULTS

4.1. **The geostrophic meridional velocities**

Fig. 3 demonstrates the geostrophic currents at the sea surface relative to 600 dbar. In conformity with results by WYRTKI (1971), the large-scale picture shows an anticyclonic motion at the sea surface. The intensive concentration of dynamic isobaths points to strong geostrophic water movements in the area between 14° and 16° S. Table I gives a general idea of the geostrophic surface velocities in the MC. Because of the deviation of section VII from the zonal direction the calculated currents have been corrected by multiplication with cosine of the angle between east-west direction and the course of profile VII.

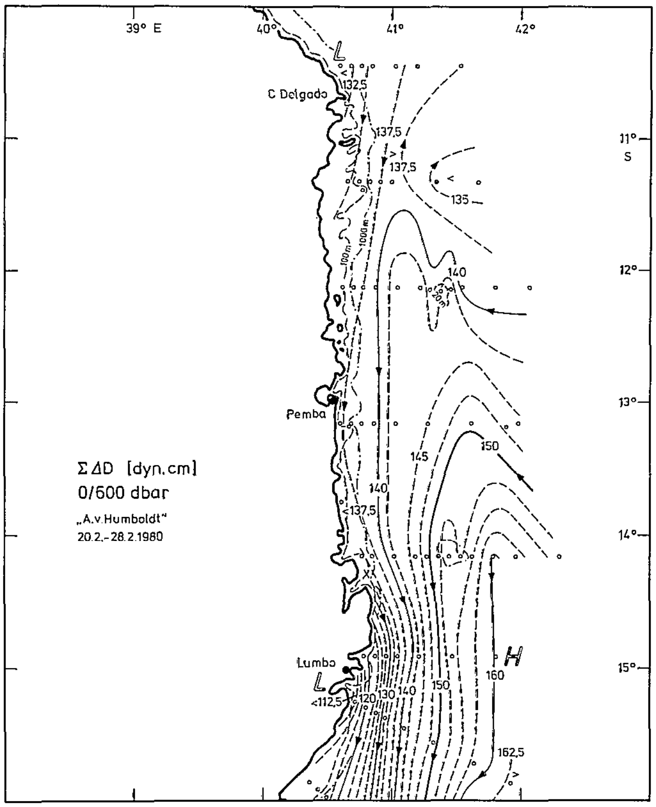

FIG. 3. — Topography of the sea surface ΣΔD with geostrophic current arrows.

Topographie dynamique de la surface ΣΔD, les flèches indiquant les courants géostrophiques.

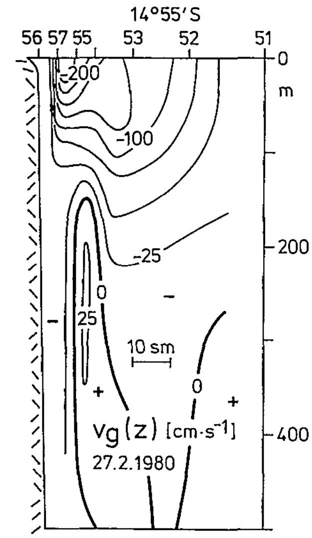

FIG. 4. — Vertical geostrophic velocity distribution v_g (z) relative to 600 dbar at profile VI.

Profil vertical de la vitesse géostrophique v_g (z) relative à 600 dbar, le long de la radiale VI.

The highest mean and maximum values of surface velocity within the MC were computed for the region between 14° and 16° S (profiles V-VII), where locally were found mean surface velocities of about 100 cm.s^{-1}, and maximum velocities of more than 200 cm.s^{-1}. In this area near the shelf edge, in the layers below the current core, underneath a depth of 100-150 m, a relative strong north-wards flowing countercurrent occured (Fig. 4). Its core was situated in a depth of about 250 m and the meridional core velocities amounted up to 60 cm.s^{-1} in profile VII, and up to 35 cm.s^{-1} in the sections VI and V.

South of 16° S the mean and maximum geostrophic surface velocities decreased with increasing geographic latitude and were twice as much lower, on an average, than in the region to the north of 16° S. Computed mean geostrophic surface velocities correspond quite well with the average current values in the "monthly charts" of the German Hydrographic Institute (DHI, 1960) derived from observations of ship's drift over many years (table II).

In accordance with the "monthly charts" of the DHI in the MC between 10° and 16° S, the lowest surface velocities in the interval $39 \leqq |\bar{v}| \leqq 51$ cm.s^{-1} occur from March to August, while the highest values lie in the range of $77 \leqq |\bar{v}| \leqq 103$ cm.s^{-1} from September to February. For this period the "monthly charts" give the following maximum velocities for every month (table III).

The far-reaching correspondence of the computed mean and maximum geostrophic surface velocities with the average mean and maximum values in the DHI-charts allows to draw the conclusion, that the current velocities in the Northern part of the MC (10°-16° S) were mainly induced by the pressure distribution relative to 600 dbar during the observation period in February 1980, and that the MC locally and seasonally shows the characteristic features of an oceanic jet stream.

4.2. Geostrophic vertical velocities at the 75 m-level

The results of the geostrophic vertical velocities computed according to equation (2) are related to the Ekman-depth D, EKMAN (1923). For the whole area between 10°30′ S and 16° S a constant value of D = 75 m was arbitrarily assumed because this depth was-nearly the top level of the seasonal pycnocline. For the level D = 75 m vertical velo-

TABLE I

Distribution of geostrophic surface velocities along the separate sections (I-VII) through the Mozambique Current in February 1980, and the mean $\bar{x}$ over (I-VII) with its standard deviation $\pm\sigma$ (positions of profiles see fig. 1)

The following symbols are used:

L^t = total width of the MC.
$-\bar{v}_g$ = mean velocities within L^t.
L^c = width of the current core within the isotach of $|v_g| \geqq 75$ cm.s^{-1}.
$|v_g|^{max}$ = maximum velocities of MC.
$-\bar{v}_g^c$ = mean velocities within L^c.

Vitesses des courants géostrophiques de surface dans les radiales I à VII effectuées en travers du Courant de Mozambique (MC) en février 1980 (cf. fig. 1).

Légendes des symboles:

L^t = largeurs totales du MC.
$-\bar{v}^g$ = vitesses moyennes dans L^t.
L^c = largeurs du noyau du courant de $|v_g| \geqq 75$ cm.s^{-1}.
$|v_g|^{max}$ = vitesses maximales du MC.
$-\bar{v}_g^c$ = vitesses moyennes dans L^c.

profile	L^t (km)	$-\bar{v}_g$ (cm.s^{-1})	L^c (km)	v_g^{max} (cm.s^{-1})	$-\bar{v}_g^c$ (cm.s^{-1})
I...........	76.4	50.8	8.4	86.2	80.6
II..........	36.3	72.2	8.0	91.9	82.6
III.........	52.8	53.9	12.9	82.1	78.5
IV..........	99.0	51.1	13.4	94.9	85.0
V...........	104.3	77.4	40.1	112.4	87.8
VI..........	128.4	135.5	71.5	213.1	141.9
VII.........	145.7	100.6	59.1	225.2	130.1
$\bar{x}$...........	91.8	77.4	30.5	126.8	98.1
$\pm\sigma$.........	39.4	31.3	26.4	64,6	26.3

TABLE II

Maximum $|v|^{max}$ and mean $\bar{v}$ southwards flowing surface velocities within the MC according to the "monthly charts" of the DHI (1960) in February, in comparison with the geostrophic currents within the MC with $|v_g|^{max}$ and $\bar{v}_g$ relative to 600 dbar in February 1980 in the sea area between 10° and 16° S.

Vitesse maximale $|v|^{max}$ et vitesse moyenne $\bar{v}$ du courant sud de surface d'après les "cartes mensuelles" du DHI (1960) pour le mois de février, comparées aux vitesses $|v_g|^{max}$ et $\bar{v}_g$ des courants géostrophiques mesurés en février 1980 par rapport à la surface 600 dbar dans la zone comprise entre 10° et 16° S.

Sea area	Monthly Charts Mean February		"A. v. Humboldt" February 1980	
10° - 16° S..........	$\|v\|^{max}$	$-\bar{v}$	$\|v_g\|^{max}$	$-\bar{v}_g$
(cm.s^{-1})............	229	77	225	77

TABLE III

Maximum surface velocities of MC within the region between 10° and 16° S from September to February, corresponding to the "monthly charts" of the DHI (1960).

Vitesses maximales du MC en surface dans la zone de 10° à 16° S, de septembre à février, d'après les "cartes mensuelles" du DHI (1960).

Month..................	IX	X	XI	XII	I	II
$\|v\|^{max}$ (cm.s^{-1})..........	220	218	257	321	-	229

cities were calculated in the range of $(0.1 \leqq w_g \leqq 10.0) \cdot 10^{-3}$ cm.s^{-1}. This order is equivalent to the values of the steady state large-scale vertical velocities estimated by SMITH (1968) for the coastal upwelling regions of eastern boundary currents, where the windstress vorticity is the causing force. In contrast to these wind-induceds upwellings over the shelves, where nutrient rich waters wells up to the sea surface, off the coast of Mozambique intermediate upward directed vertical currents, forced by the influence of planetary vorticity on the MC, occurred seaward the shelf edge (Fig. 5). North of 14° S the zonal extent of the area with ascending water movements was on an average 45-60 km. The intermediate zone with vertical velocities in the range of $(5 \leqq +w_g \leqq 10) \cdot 10^{-3}$ cm.s^{-1} extended along the coastline, at a distance from the coast of 20-45 km, in the shape of a narrow band with a width of 15-30 km.

East of this band a zone with downward directed intermediate vertical currents was developed, in which the vertical velocities at $z = D$ amounted to maximum values of more than -10^{-2} cm.s^{-1}.

Between 14° and 16° S, the width of the area with intermediate upward directed vertical currents considerably increased and amounted to 120-130 km. The zone with vertical velocities of $(5 \leqq +w_g \leqq 10) \cdot 10^{-3}$ cm.s^{-1} came close to the shelf edge and was divided into two parts by the effects of countercurrents, described in section 4.1.

The region with intermediate descending water motions east of it was only incompletely investigated by our measurements. In conformity with the decrease of the meridional current component of MC south of 16° S, with the exception of isolated cases, the w_g, caused by v_g were considerably lower and amounted only to values of about $1 \cdot 10^{-3}$ cm.s^{-1} and less. For the description of the effects of intermediate $(+w_g)$ on the micro-nutrient distribution in the euphotic layer, the regional distribution of NO_3-N at $D = 75$ m was delineated in fig. 6. Figure 6 demonstrates that these effects were remarkably unimportant northern of 14° S. In correspondence with fig. 5, within the coastal parallel

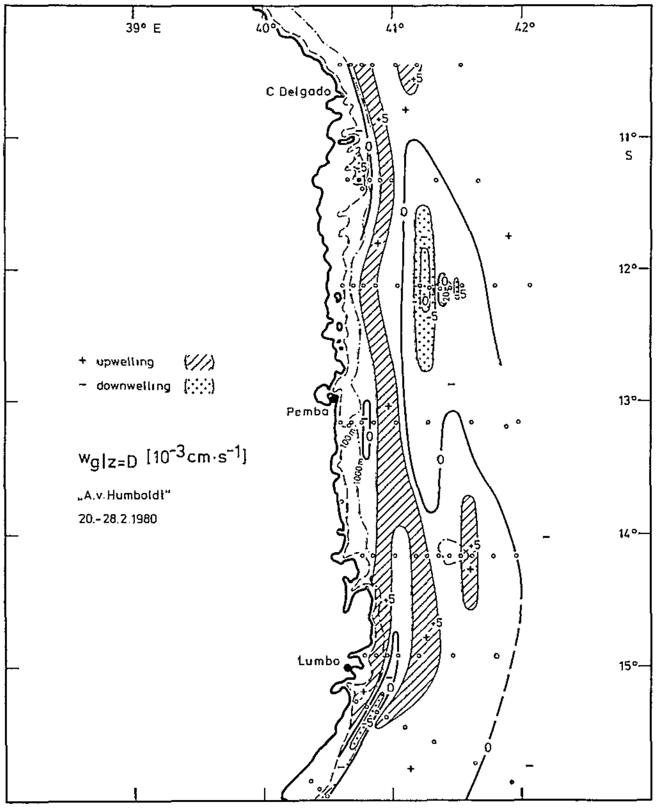

FIG. 5. — Isotachs of the geostrophic vertical velocity w_g at the level D = 75 m relative to 600 dbar.

Carte des isolignes de la vitesse géostrophique ascensionnelle w^g relative à 600 dbar, à la profondeur D = 75 m.

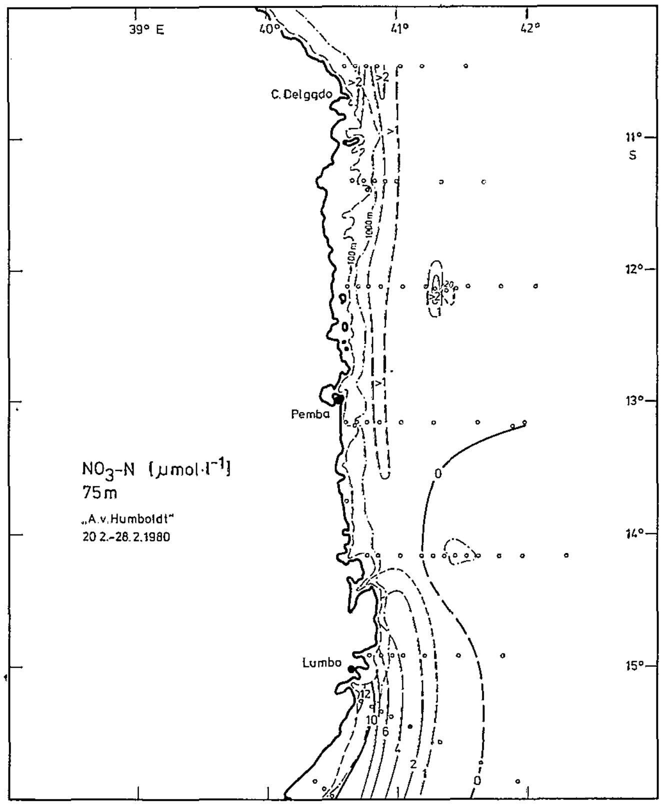

FIG. 6. — Horizontal distribution of NO_3-N at depth D = 75 m.

Répartition horizontale des NO_3-N à la profondeur D = 75 m.

orientated band of drastic $+w_g$ at D = 75 m, a narrow zone was found with an extremely small enrichment of micro-nutrients, in which the NO_3-N —content was somewhat higer than 1 µmol per litre. The isolines of physical and chemical parameters along the zonal sections within this area, here not reproduced, demonstrate, that the upward directed currents ($+w_g$) are limited to the water layers underneath the assumed depth D = 75 m. However, between 14° S and 16° S, the intermediate ($+w_g$)-currents carried up considerably quantities of micronutrients into the euphotic layer. Here, NO_3-N-contents of more than 10-12 µmol per litre were locally measured at D = 75 m.

5. CONCLUSIONS

From the investigations with the R/V "A. v. Humboldt" in February 1980 the following conclusions were drawn for the northern part of the Mozambique Current between 10°30′ S and 16° S:

— The Mozambique Current (MC) was in geostrophic balance.

— The computed geostrophic surface velocities relative to the 600 dbar-level correspond to the mean and maximum values of historical shipdrift observations.

— Within an average width of the current core of 30 km, mean geostrophic core velocities of about 100 $cm.s^{-1}$ and maximum velocities of more than 200 $cm.s^{-1}$ had been locally observed.

— The MC showed the characteristic features of an oceanic jet stream during this season.

— The effects of the planetary vorticity on the MC with respect to the vertical velocities at the depth D = 75 m are of the same order of magnitude (10^{-3} $cm.s^{-1}$) as the effects of wind-stress vorticity on coastal upwellings in eastern boundary currents.

— The maximum upward directed motions had been observed along the MC-core.

— The intermediate upward directed currents locally demonstrate pronounced effects with regard to the micro-nutrient distribution in the euphotic layer.

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APPENDIX

A detailed description of the accurracy of computations by the dynamic method was given by FOMIN (1964). With respect to details it is referred to this treatise. In conformity with FOMIN, the maximum error dh in the computation of conventional dynamic depth his directly proportional to the error in the determination of specific volume anomaly d (δ) and pressure difference between the chosen reference level p = 600 dbar and the sea surface p = 0.

$$(A1.)/dh = p \,.\, d \;\; (\delta)$$

For the mean deviations of the sensor data from thermometer measurements and salinometer determinations, see also section 2; the error in specific volume anomaly was determined to be $\pm 1{,}8 \,.\, 10^{-5}$ cm^3 g^{-1}. From expression (A 1.) it ensues that the maximum error of dynamic depth anomaly was ± 1,08 dyn cm. With hypothesis of a normal distribution of errors in 90 % of the cases, the error in the computation of dynamic depth does not exeed half the maximum error, we can then assume that the error in the computation of dynamic depth anomaly was in the order of ± 0,54 dyn cm. The maximum error of current velocity (v_g) is estimated by the expression (A 2.).

$$(A2.)/dv_g = 2d(\Delta\tilde{D})/f.L$$

It derives first of all from the error in the computation of differences of dynamic depth anomaly d ($\Delta\tilde{D}$) between two neighbour stations separated by the distance L. Because, according to FOMIN (1964), the actual error of the difference d ($\Delta\tilde{D}$) is only about one-third of its maximum value in the sense of its probability of occurrence, this error was assumed to be ± 0,72 dyn cm. The actual mean error in the current velocity v_g amounted to $\overline{dv_g} = 12{,}0 \pm 1{,}6$ cm . s^{-1} with a range of confidence according to the t-distribution by the probability of 95 % in th sea area between 10° 30′ S and 16° S. The error of the vertical velocity w_g is dw_g. This value depends only on the error of meridional velocity dv_g, not on the constant distance between the selected reference level of 600 m and the surface D = 75 m.

$$(A3.)/dw_g \approx \beta \,.\, dv_g \,.\, (525m)/f$$

Taking in account the same probability of error as mentioned above, $\overline{dw_g}$ amounted to $(3{,}5 \pm 0{,}9) \,.\, 10^{-3}$ cm . s^{-1} in the region between 10° 30′ S and 16° S: v_g and w_g were discussed only if their values were over those computed errors.

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