A meandering intermediate front North-West off Cape Verde Islands

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Abstract

From literature, a short overview is given on meso-scale eddy-like structures in the subtropical Atlantic off Northwest Africa.

Preliminary results are described from oceanographic measurements of r/v « A.v. Humboldt » in the zone between the Canary Current and the North Equatorial Current north-west off Cape Verde Islands during October/ November 1982.

The observations show a superposition of local forced Ekman dynamics within the oceanic top layer for a time scale of about 16 days and for a meridional scale of about 160 kilometres on intermediate eddy-like structures along a meridional front zone with quasi-stationary nature in depths between 100 dbar and 500 dbar pressure level.

Because the production of relative vorticity is higher, at least by a factor of two, within the intermediate layer between 300 dbar and 600 dbar, than the local vorticity contribution from the wind stress curl within the 70 dbar top layer, it is concluded that the baroclinic instability of an intermediate « mean flow » is an essential energy source for such eddy-like features.

It is speculated from the vertical structure of measured currents and from the literature that the patterned « mean flow » is part of a meridional wave crest which is formed by the second or third vertical mode of a very low-frequent Rossby wave likely forced by annual or by semi-annual fluctuations of north-east trades.

Within the front zone, mixed water is observed resulting from the mixing of the North Atlantic Central Water (NACW) with the South Atlantic Central Water (SACW) while above these layers properties of Sargasso Water (SW) are found. Based on water properties in intermediate layers, a hint is given that the investigation area is influenced by waters from the North Atlantic Current system within a subsurface layer above the 18 °C isotherm, while it is influenced too by waters from the equatorial current system in layers between the isotherms of 12 °C and 15 °C respectively.

Key words : Intermediate fronts — Subsurface currents — Eddies — Central waters — Upwelling — Canary Current — Northeast Central Atlantic.

Résumé

Un front intermédiaire en forme de méandre au nord-ouest des Iles du Cap Vert

Une brève revue de la littérature relative aux structures de type tourbillonnaire, à méso-échelle, est donnée pour la région de l'Atlantique subtropical, au large de l'Afrique du Nord-Ouest.

Les résultats sont présentés, d'une croisière du N.-O. « A.v. Humboldt » réalisée dans la zone comprise entre le Courant des Canaries et le Courant Nord Equatorial, au Nord-Ouest des Iles du Cap Vert, en octobre-novembre 1982.

Les observations montrent qu'une dynamique de type forçage local d'Ekman sur la couche superficielle (échelle de temps: environ 16 jours; échelle spatiale méridienne: environ 160 km) se situe au-dessus d'une structure intermédiaire de type tourbillonnaire, le long d'une zone frontale méridienne, de nature quasi-stationnaire, à une profondeur barométrique comprise entre 100 et 500 dbar.

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Parce que, dans la couche intermédiaire, entre 300 et 600 dbar, la production de vorticité relative est supérieure (au moins d'un facteur 2) à la contribution locale de vorticité due au rotationnel des tensions de vent dans la couche située au-dessus du niveau de 70 dbar, on en conclut que l'instabilité barocline d'un écoulement moyen intermédiaire est une source d'énergie essentielle pour expliquer de tels phénomènes tourbillonnaires.

D'après la structure verticale des courants mesurés et selon les données de la littérature, cette disposition de flux moyen semble être une partie de la crête d'une onde méridienne formée à partir des 2e et 3e modes d'une onde de Rossby de très basse fréquence, probablement forcée par les fluctuations annuelles ou semi-annuelles des alizés de Nord-Est.

Dans la zone de front, on observe un mélange de l'Eau Nord Atlantique Centrale et de l'Eau Sud Atlantique Centrale, alors qu'au-dessus de ces couches, on trouve des eaux présentant les caractéristiques des eaux des Sargasses. En se fondant sur les propriétés des eaux des couches intermédiaires, une indication est donnée selon laquelle la zone étudiée est influencée par des eaux du système du Courant Nord Atlantique dans la couche subsuperficielle, au-dessus de l'isotherme 18 °C, et subit également l'influence des eaux du système du Courant Equatorial dans la couche comprise entre les isothermes 12 °C et 15 °C.

Mots-clés : Fronts intermédiaires — Courants subsuperficiels — Tourbillons — Eaux centrales — Upwelling — Courant des Canaries — Atlantique central nord-est.

Zusammenfassung

Es werden ozeanographische Beobachtungen aus der 1 500 dbar Deckschicht vorgestellt, die aus dem Untersuchungsgebiet nord-westlich der Kap Verden während Oktober/November 1982 erhalten wurden.

Für die Existenz barokliner wirbelartiger Strom- und Massenfeldmuster zeigt sich hier in der Schicht zwischen 100 dbar und 500 dbar eine beträchtliche Evidenz. Diese Erscheinungen sind im Inneren durch Mischwassereigenschaften mit erhöhtem Gehalt von Südatlantichem Zentralwasser (SACW) ausgezeichnet. Es wird angenommen, daß derartige intermediäre Muster durch eine meridional verlaufende Front erzeugt werden, die an der Nordgrenze des Nordostpassates lokal gestört wird und dort wirbelartige Gebilde hervorruft.

Aus Literaturangaben und den erörterten Beobachtungsergebnissen wird hypothetisiert, daß diese intermediären Fronten durch meridionale Wellenkämme der zweiten und/oder dritten vertikalen Moden von sehr niederfrequenten Rossby-Wellen herrühren, die durch die jährlichen oder halbjährlichen Windfluktuationen angeregt wurden. Derartige Wellen werden wahrscheinlich aus dem Gebiet des polwärts setzenden Unterstromes vor dem Kontinentalabhang in das Untersuchungsgebiet abgestrahlt.

1. INTRODUCTION

A great part of storage of energy in the ocean occurs on temporal scales of weeks to months and spatial scales of few tens to some hundred of kilometres.

Frequently, the picture of these meso-scale events is noted not only by eddies, but also by meandering both oceanic surface fronts and intermediate fronts. The latter are dynamically connected with low-frequency baroclinic Rossby waves.

The dynamics of such eddy-like structures are nearly characterized by a geostrophic momentum balance, especially in the regions of the open ocean.

While extensive observations of such geostrophic eddies have been carried out in western boundary currents (WBC), for instance by the MODE-GROUP (1978) in the Gulf Stream, comparatively few detailed observations of meso-scale eddies have been reported from areas of eastern boundary currents (EBC).

On the other hand, the relative vorticity is small in a broad and weak flow from east to west, given by the EBC, but the relative vorticity is high in a narrow and strong flow from west to east, given by the WBC. This fundamental conclusion of Fofonoff (1954) underlines the probability that the dynamics of baroclinic meso-scale features are different in areas of WBC from these in EBC regions in respect to their response on the forcing mechanism. However, the corresponding pictures of their spatial and temporal structures give a hint to analogous kinematics both in WBC and in EBC. Recently some observations of meso-scale eddies and meso-scale oceanic fronts are presented in literature from the EBC area of the Canary Current off North-West Africa.

The shipborne observations by Kort (1982) show that the eddy dislocation is mainly directed to decreasing water depths. Such a response can be understood by the action of the joint effect of the baroclinity and the bottom relief on large scale horizontal pressure gradients.

More details are presented by a collection of recent papers (Oceanological Researches No. 36 (1984) of the Academy of Sciences of the USSR, Soviet Geophysical Committee). Here, many aspects are studied with respect to influences of bottom topography on eddy-like motions in the area between 27°/34° N and 30°/36° W.

The analysis of current measurements by HOGG and SCHMITZ (1980) suggests the evidence of low frequent motions in a period range of 19 up to 96 days which are weakly bottom intensified at the Gibbs Fracture Zone. This range lies outside the typical time scale of plane baroclinic Rossby waves of low mode number. Obviously, topographic Rossby waves play an important role in areas with strong topographic irregularities as it is given in the region of Mid-Atlantic Ridge.

Furthermore, the North Atlantic Current produces geostrophic eddies near the Gibbs Fracture Zone. Their diameter is estimated by MEINCKE (1982) in order of 100 kilometres, while the time scale lies in order of several months. In comparison with results from OWENS and HOGG (1980), one can expect that the advection of relative vorticity by the branch of North Atlantic Current into the region south of the Azores is an important process for the eddy generation. These authors show that the vorticity balance is primarily controlled by the advection of relative vorticity and by vertical vortex stretching around a seamount centred at 36° N, 55° W, in a WBC branch.

On the other hand, KÄSE and SIEDLER (1982) describe a subtropical front with eddy-like structures south-east of Azores near the position of 34° N, 22° W, in early 1982. This position lies in the atmospheric convergence zone associated with the confluence of currents at the sea surface. The authors conclude the meandering oceanic front is induced by a branch of North Atlantic Current described by DIETRICH *et al*, (1975). The strong meandering may be produced by quasi-stationary Rossby waves.

The map of the potential energy (15 °C isotherm) by DANTZLER (1977) shows analogical energy levels in the investigation area of KÄSE and SIEDLER (1982) as well as in the area under consideration north-west off Cape Verde Islands. Therefore, corresponding flow kinematics are expected in both areas. According to KRAUSS and WUEBBER (1982), it is assumed that the Rossby waves generated in a relative small section of Atlantic, as it is given within the trade belt, will propagate out of the forcing area towards the west with a little tendency to north. This fact follows from their investigations with a wind forcing of the annual signal. The resulting numerical calculations are centred near 18° N off Northwest Africa.

It is interesting to note, the amplitude of the northward travelling wave is less damped than the southward propagating one. Furthermore, the northward travelling wave becomes the dominating signal within the interior of eastern Atlantic. Their estimated wave length is about 2 000 km for plausible assumptions.

The authors conclude that such plane wave may play an essential role south of the Azores. Moreover, it is fascinating that the turning point of vanishing group velocity is located in the dispersion relationship near the annual forcing frequency for the second mode with an estimated wave length of about 150 km and with a period of nearly 240 days.

Moreover, from an analysis of long time series of atmospheric pressure and winds along the coast of Northwest Africa, it was shown by MICHELCHEN (1981) that the energy densities of the half-year period predominate over the energy level of one year peaks in the zone between the trades and calms from Saint-Louis (16° N) down to Banjul (13°20' N). Therefore, we can expect a semi-annual forcing too for Rossby waves in this region. Because it is a commonly accepted notion that the energy is accumulated under disappearing energy transports, i.e. if the group velocity is zero, it is likely that an energy storage is possible by meso oceanic space scales for such modes of Rossby waves.

From the USSR experiment "POLYGON-70", KOSHLYAKOV and GRACHEV (1973) report the existence of an anticyclonic eddy in an area around the position of 16°30' N, 33°30' W. This eddy was detected at all depths from 25 m down to 1 500 m. From the comparison of measured currents with geostrophic currents, it was concluded that this kind of eddy is of quasi-geostrophic nature. Following characteristics are outlined:

- the smaller eddy dimension was 90 km,
- the larger eddy dimension was 200 km,
- the average orbital velocity was in the velocity range of 20 $cm.s^{-1}$ up to 25 $cm.s^{-1}$ within the 200 m/500 m layer and it was about 10 $cm.s^{-1}$ at 1 500 m,
- with respect to a wave-like eddy motion, the wave length was 360 km while the mean drift speed of 3.1 $km.d^{-1}$ (to 215° from north) was yielding a time scale of 116 days.

It is pointed out that the spatial structure of this eddy was influenced by local processes. This conclusion is in accordance with results from numerical investigations by OWENS and BRETHERTON (1978) for a WBC area (region of the Mid-Ocean Dynamics Experiment). Moreover, the efficiency of the southern and of the northern boundary of north-east trades is more marked in the east Atlantic than in the west Atlantic (see monthly charts of the German Hydrographic Institute, DHI, 1956). It is a commonly accepted notion too that the regions with large scale shifting atmospheric fronts are source of very low frequency Rossby waves in the ocean.

From this viewpoint, the probability is high to find meso-scale baroclinic eddies in the transitional zone between the Canary Current and the North Equatorial Current, e.g. in the mean zone of the northern boundary of north-east trades, where the large scale pressure gradients are drastically disturbed by the discontinuous conditions at the sea surface. Caused by the vertical stratification of the ocean, an intense division of energy results in such zones, not only in favour of the barotropic motion, but also in favour of different baroclinic modes. For instance, typical values for the barotropic and for the first three baroclinic modes are given by PHILANDER (1978) for mid-latitudes and for the equatorial region of the Atlantic. According to these investigations the zero points of the second vertical mode are nearly located at the levels of 500 m and of 3 000 m, while the zeros of the third mode are found at 200 m, 1 000 m and at 3 300 m in which the 1 000 m level is also the zero point for the first mode at mid-latitudes. In the following it is assumed that the zeros unessentially differ from these levels for mean conditions in the investigation area.

On the other hand, for the production of subsurface baroclinic eddies, the intermediate undercurrents may be important in the same manner as the branch of the North Atlantic Current south of the Azores with respect to advection of relative vorticity. It is expected that their variability is high because they hardly persist a few weeks as they are rapidly dispersed by long westward travelling Rossby waves. In this sense, the intermediate undercurrents are a dynamical part of very low-frequent Rossby waves of higher modes in the open ocean.

The interaction between the bottom topography and the stratification involves a horizontal trapping scale which is denoted sometimes are baroclinic deformations radius. This scale is in the order of some tens of kilometres.

Furthermore, DEMIN *et al.* (1981) used a diagnostic model to investigate the outflow of South Atlantic Central Water (SACW) from the North Equatorial Undercurrent into the region of the Guinea Dome which is located over the Gambia Abyssal Plain, near the position of 12° N, 22° W. Outflowing from the Guinea Dome, these waters are feeding two flow branches to north. The eastern branch is connected with the upwelling undercurrent off the continental shelf, while the western branch is part of a large cyclonic motion around the Cape Verde Islands. This gyre is topographically controlled up to the 100 m level. Among other things, the SACW is characterized by a linear temperature-salinity (T-S) relationship in layers between 100 m and 300 m, according to SVERDRUP *et al.* (1952). The North Atlantic Central Water (NACW) is defined by another linear relationship too. This kind of waters spreads out to south. Both central water masses are separated by an internal front zone. According to VOITURIEZ and CHUCHLA (1978), the SACW is a permanent phenomenon in the region between the Cape Verde Islands and the African coast up to a latitude of 15° N during the whole year. A review was compiled by HAGEN and SCHEMAINDA (1984) with respect to the SACW extension north of 15° N into the Upwelling Undercurrent and into the area under consideration.

On this background, an oceanographic description of baroclinic eddy-like structures is presented in the following from a region without strong irregularities of bottom topography north-west off the Cape Verde Islands.

2. DATA

The r/v "A.v. Humboldt" of the GDR Academy of Sciences undertook an exploratory voyage to the region between the Canary Current and the North Equatorial Current in October/November 1982 (1). The area of investigation lies north of the Cape Verde Islands in a zone of surface divergence (Fig. 1). It is frequently denoted as Cape Verde Divergence.

The wind velocity and the wind direction were observed about 10 meters above the sea surface at all stations.

The wind values were resolved into their components. The rotation of the coordinate system by 33° from north was taken into account in order to estimate the along section component and the across section component with respect to the climatological mean wind direction. The same procedure was carried out for the measured current velocities from the drifting ship. The current meter used during the experiment was described by MÖCKEL and WILL (1980). The measurements were performed by a step by step procedure in selected pressure levels, given in the legend of Fig. 1. The resulting currents were reduced to the 600 dbar reference level. The estimation of the ship's drift was detected by satellite navigation at such stations where two satellites passed through the position during the station time. Generally, the components are noted by the symbol (^) for the rotated axis, while the notation is used without this earmark for the usual components with the x-axis to east and the y-axis to north.

(1) A preliminary report on this cruise was given by H.U. LASS at the 2nd meeting of the "CCCO Tropical Atlantic Panel" in Paris (UNESCO), 10 and 11 February 1983.

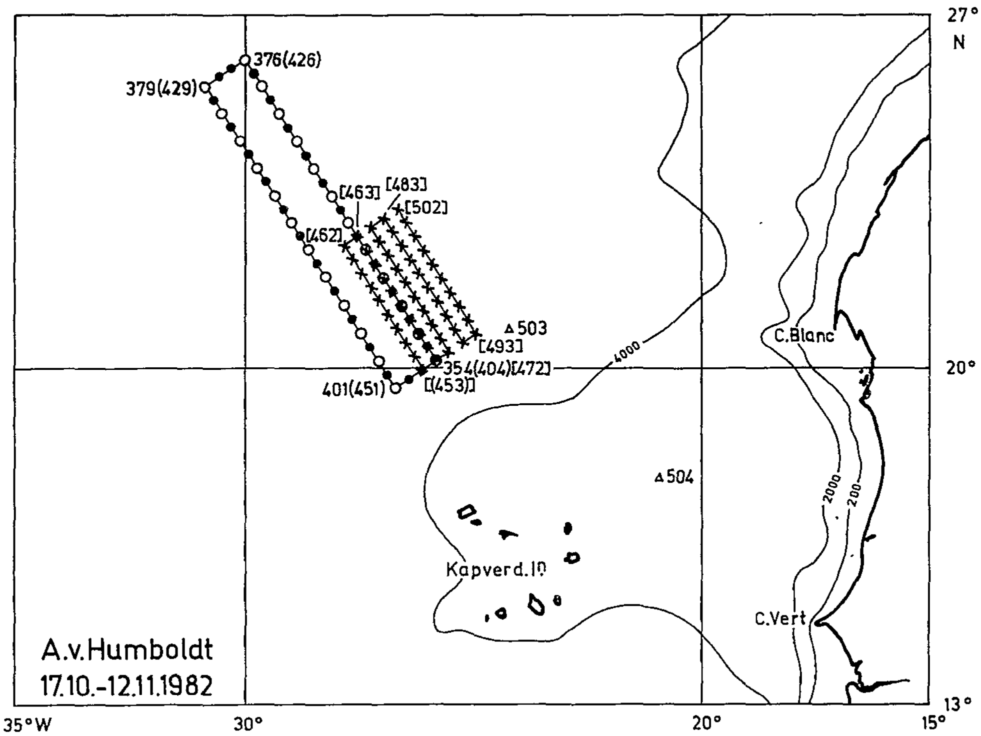

FIG. 1. — Track chart of r/v "A.v.Humboldt" over a bottom topography with isobaths in meters during October/November 1982 The first run is denoted by station numbers 354 up to 403, while the second run is marked by the numbers from 404 to 453. The supplement station grid is given by the numbers 453 to 502. The used symbols:

● Stations with oceanographic observations by the "OM-75" with a lowering velocity of -.5 $m.s^{-1}$ from the sea surface down to 620 dbar level and with the velocity of nearly 1 $m.s^{-1}$ from 580 dbar level to 1 500 dbar horizon;

O Stations with additional current measurements at the pressure levels of 20, 30, 40, 50, 60, 80, 100, 125, 200, 250, 400 300, 500, 600 dbar from the drifting ship and chemical samples of PO_4-P and NO_3-N at the levels of 1, 25, 50, 75, 100, 200, 500, 750, 1 000, 1 250, 1 500 dbar;

× "OM-75" measurements from the sea surface down to the 1 000 dbar level with a lowering velocity of 1 $m.s^{-1}$ with water samples for the determination of salinity, PO_4-P, NO_3-N at the levels of 50, 100, 150, 200, 250, 300, 350, 400, 450, 500 dbar

Itinéraire du N.O. « A.v. Humboldt » dans une zone à bathymétrie complexe, en octobre-novembre 1982 (isobathes en mètres) Premier parcours : stations 354 à 403 ; second parcours : stations 404 à 453 ; le réseau de stations supplémentaire est numéroté de 453 à 502

Symboles :

● *Stations océanographiques à la sonde OM-75 ; vitesse de descente : 0,5 $m.s^{-1}$ de la surface au niveau 620 dbar, et 1 $m.s^{-1}$ du niveau 580 dbar au niveau 1 500 dbar*

O *Stations auxquelles sont, de plus, effectuées des mesures de courant aux niveaux de pression de 20, 30, 40, 50, 60, 80, 100, 125, 200, 250, 300, 400, 500, 600 dbar, à partir du navire en dérive, et des prélèvements pour analyse de PO_4-P et NO_3-N, aux niveaux 1, 25, 50, 75, 100, 200, 500, 750, 1 000, 1 250, 1 500 dbar*

× *Mesures à la sonde « OM-75 », de la surface du niveau de 1000 dbar, avec une vitesse de descente de 1 $m.s^{-1}$, et échantillonnage d'eau pour détermination de la salinité, de PO_4-P et NO_3-N aux niveaux 50, 100, 150, 200, 250, 300, 350, 400, 450, 500 dbar*

The wind stress is estimated by the formula

$$\tau^{x,y} = \rho_a \cdot C_d \cdot |\vec{V}| \cdot (U, V)$$

with the mean air density $\rho_a = 1.226$ $kg.m^{-3}$, the drag coefficient $C_d = 1.23 \cdot 10^{-3}$. The pressure, temperature, conductivity, sound velocity, oxygen content were measured continuously by means of the measuring system "OM-75" while lowering it. The last has been described in detail by MÖCKEL (1980).

For instance, the temperature values were controlled by two reversing thermometers at each station. The analogous procedure was carried out for the salinity by salinometer measurements from selected horizons as it is outlined in the legend of Fig. 1. It is to note that we don't exclude aliasing effects on the measurements along the oceanographic sections. These errors are produced by high-frequent processes which are not caught by the procedure of one ship measurements with a station distance of 20 nm. In a first approximation step, it is assumed

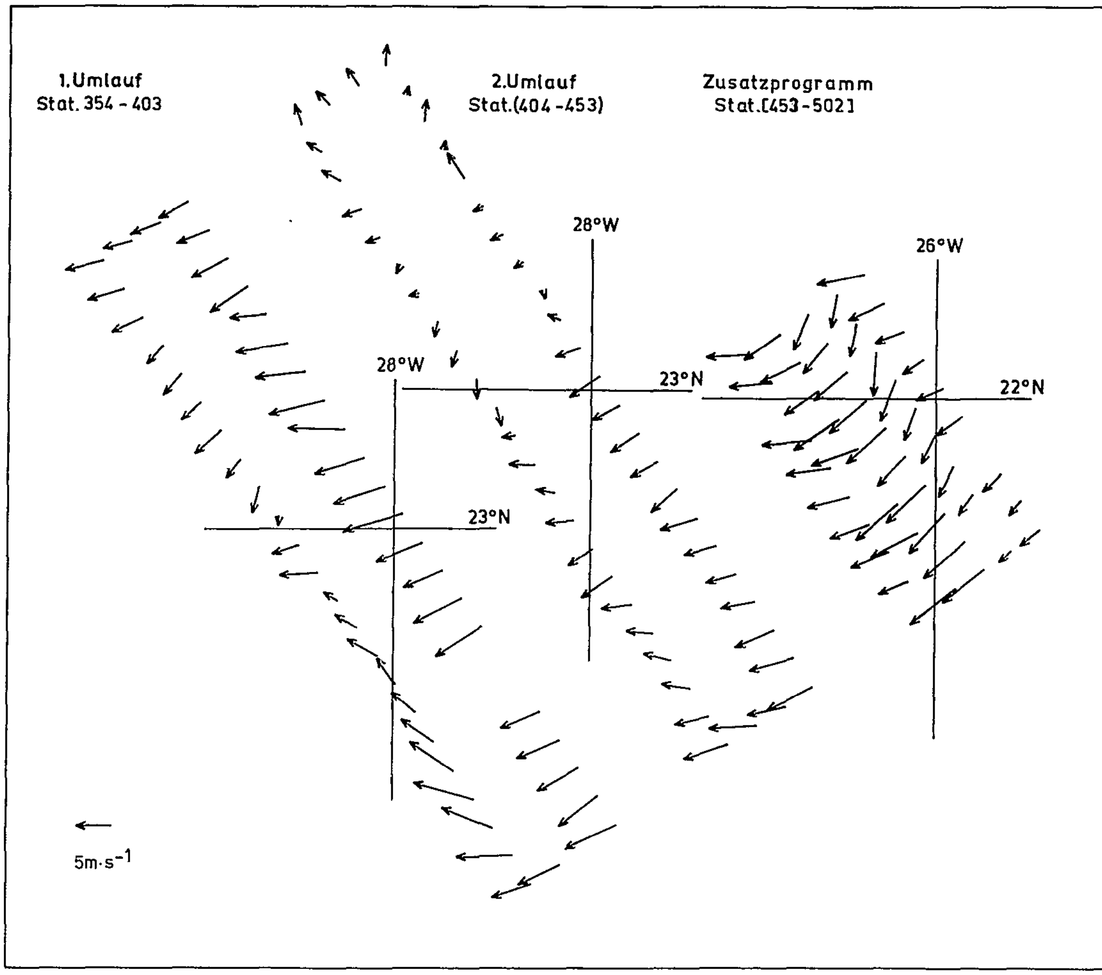

FIG. 2. — Wind arrows during the three programme parts
Représentation des vents au cours des trois parties du programme

a sufficient signal noise relation, because the investigations are carried out in a region far off coasts and islands.

3. PRELIMINARY RESULTS

3.1. North-east trades and air pressure

The mean northern boundary of the north-east trades lies at longitude of 27° W and at latitude of 22°30' N in October. This atmospheric discontinuity zone shifts to south down to 20° N from October to November. This fact follows the monthly charts (DHI, 1956).

The local wind conditions are given in Fig. 2.

The winds are highly variable, not only in space, but also in time. The winds were stronger in south, with a uniform direction to south-west, than in north of the sections where weak wind speeds prevailed into different directions. It is to speculate from Fig. 2 that the northern boundary of north-east trades (NBNET) was located north of the investigation area during the first oceanographic run, but it was placed at the latitude of about 22°30' N during the second run. This fact is indicated by an abrupt changing of the wind direction and of the decreased wind speeds, as it is demonstrated in Fig. 2. This location of the atmospheric frontal zone corresponds to the climatological October position of NBNET (compare to Fig. 3).

The actual NBNET meridionally pulsates in time. This conclusion is affirmed by the time behaviour of the distribution of air pressure along the sections. An example is presented in Fig. 3. At the selected section, compare Fig. 1 with respect to

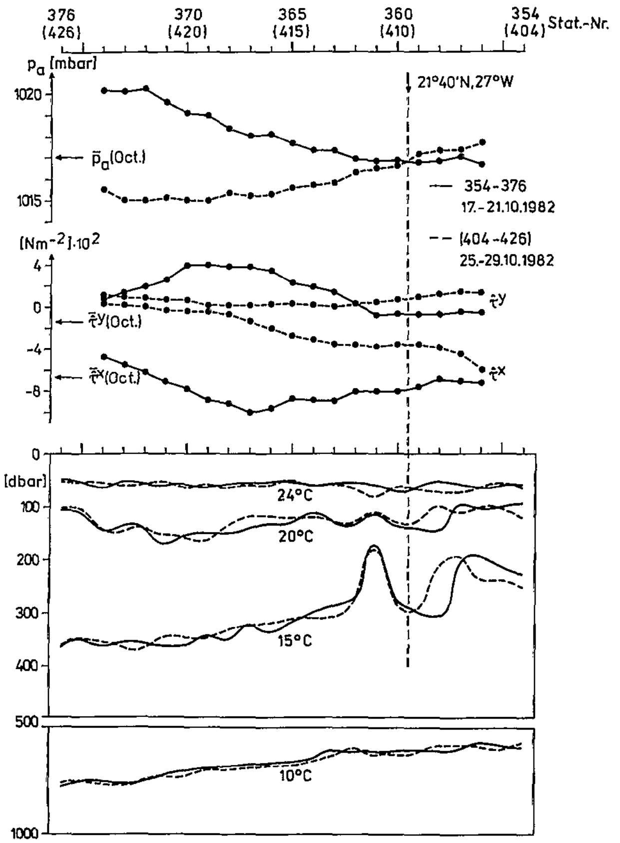

FIG. 3. — Eight day time response of the atmospheric pressure P_a in comparison with its climatological mean value for October $\bar{p}_a$ (Oct.) at the position of the northern boundary of north-east trades near 21°40' N, 27° W (broken line)
The along section wind stress $\hat{\tau}^y$ and the across section wind stress $\hat{\tau}^x$ are respectively given with their October means from the monthly charts of DHI (1956). The pressure levels of selected isotherms are compared for the two runs

*Réponse sur huit jours de la pression atmosphérique comparée à sa valeur moyenne climatique en octobre, à la limite nord des alizés de Nord-Est, près de 21° 40' N, 27° W (ligne en tireté)
Les tensions du vent dans la direction du parcours $\hat{\tau}^y$ et selon l'axe transverse $\hat{\tau}^x$ sont données d'après les moyennes d'octobre fournies par les cartes mensuelles du DHI (1956). Les niveaux de pression de quelques isothermes sont comparés pour les deux parcours*

section orientation, the air pressure fluctuates with 5 hPa in north, but it only varies with 1 hPa in south between the two observation periods. No pressure differences were measured at the latitude of mean NBNET.

The time variation of air pressure increases on both sides of the atmospheric front zone in different way. If it is assumed that the time lag of 8 days between the two oceanographic runs corresponds to a semi-period, it results a fluctuation period of about 16 d.

These observations are in confined accordance with the wind and with the atmospheric pressure records by KOSHLYAKOV and GRACHEV (1973), which show a significant peak for periods of about 6 days, not only in the spectrum of wind speed fluctuations, but also in spectrum of atmospheric pressure variations. The across section wind stress component $\hat{\tau}^x$ reacts stronger on the corresponding atmospheric pressure fluctuations than the along section component $\hat{\tau}^y$. This is in accordance with the large scale atmospheric pressure distribution by the North Atlantic high and the equatorial low pressure belt.

3.2. **Intermediate thermic « bumps »**

Fig. 3 shows the vertical displacement of selected isotherms between the two sections runs.

A significant reaction of the isotherm depths on the local atmospheric pulsation is visually not given. However, the intermediate vertical bumps of the 15 °C isotherm are trapped on both sides of the mean position of NBNET.

One bump was locally fixed at station 361/411 which is placed north of the climatological NBNET position (compare Fig. 3 with Fig. 4), while an other one was slightly shifted from south up to the mean position of atmospheric front zone. The dislocation speed of about 5 km.d^{-1} results from the station spacing of 40 km and from the time difference of 8 d between the observations. This averaged speed shows a drastic discrepancy to the usual values of free Rossby waves with low mode number. Therefore, the dynamics of free baroclinic and low frequency waves are excluded for an explanation of the observed phenomena. On the other hand, the estimated shifting of 5 km.d^{-1} corresponds well to the results of the "POLYGON-70" experiment. Caused by this, a hint is given for analogical motion kinematics in both areas. Furthermore, Fig. 4 shows that the intermediate phenomena are indicated by the drastic vertical displacements of isotherms between 20 °C and 11 °C, especially in south of this section. The vertical deformation of isotherms is roughly fivefold smaller at the northern stations. Generally, the isotherms which are lower than 20 °C tilt from low pressure levels in south to high pressure levels in north along the section. This fact corresponds to the influence of geostrophical adjustment of mass field on the large scale current directed from north-east to south-west (cf. STRAMMA, 1984). Contrarily to this larger scale inclination of the thermic structure along the section, the wind mixed layer is roughly demarcated from deeper layers by the isotherm of 24 °C which indicates the limitation of homogeneous top layer at about 50 dbar in Fig. 3 and in Fig. 4.

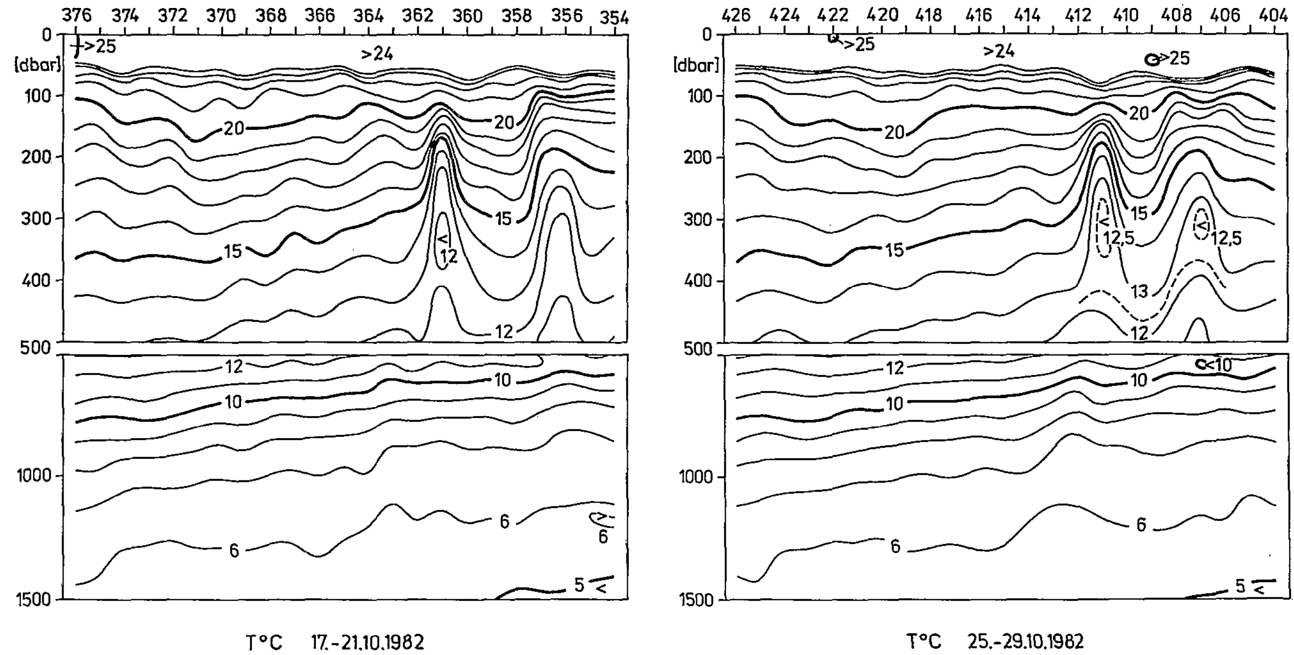

FIG. 4. — Two temperature sections through the transitional zone between the Canary Current and the North Equatorial Current with a station distance of 20 nm at the same positions. (a) during the first run; (b) during the second run

(Note that the vertical pressure axis changes the scale below 500 dbar and the station numbers are given in Fig. 1)

Deux coupes de température, relevées sur la même radiale, avec une station tous les 20 nm, à travers la zone de transition entre le Courant des Canaries et le Courant Nord Equatorial: (a) *premier parcours;* (b) *second parcours*

(Noter que l'échelle des pressions change au-delà de 500 dbar; la numérotation des stations est donnée à la fig. 1)

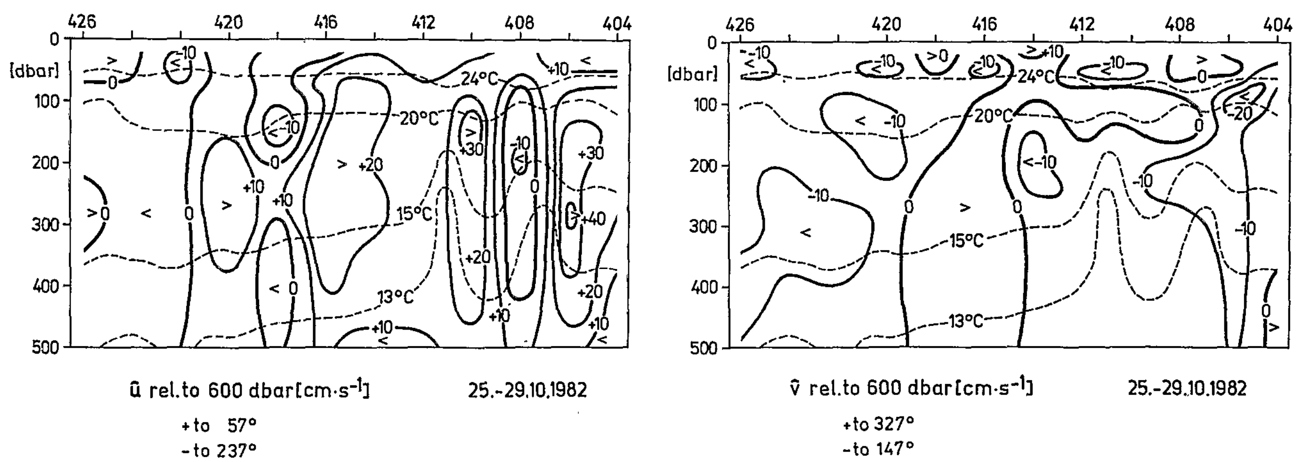

FIG. 5. — Currents components in the rotated coordinate system, (a) the reduced across section component û; (b) the reduced along section component v̂

The broken lines mark the course of selected isotherms corresponding to Fig. 4b

(Note that the station distance was 40 nm for the current measurements but 20 nm for the oceanographic observations)

Composantes du courant dans le système de coordonnées, après rotation. (a) *la composante transversale réduite û;* (b) *la composante longitudinale réduite v̂*

Les lignes en tireté représentent les isothermes choisis correspondant à la Fig. 4b

(Noter la distance de 40 nm entre deux stations de courantométrie et de 20 nm entre deux stations hydrologiques)

3.3. Vertical current structures

A comparison between the along section structure of selected isotherms and the measured currents is given in Fig. 5. The values of across section components are commonly higher, nearly by a factor of three than the corresponding values of along section components, especially within the baroclinic intermediate features (compare Fig. 5a, b).

For example, Fig. 5a shows core speeds between -10 $cm.s^{-1}$ (to 237°) and 40 $cm.s^{-1}$ (to 57°) relative to the 600 dbar reference level in the southern corner. The velocity cores are centered in depths between the 100 dbar and 500 dbar pressure level there, where the plotted isotherms indicate a crest factor of their horizontal gradients, especially between the stations 406/412 and between 418/420 in Fig. 5. By this, a hint is given for the geostrophic nature of motions within the indicated baroclinic events. The estimated core velocities manifest the same order as the mean orbital speed of about 20 $cm.s^{-1}$ at 200 m during the "POLYGON-70" experiment.

Because the wind produced currents are bounded within the uppermost 20-40 dbar layer, it is to speculate from the accordance between the observed vertical current structure and the vertical mode structure given by PHILANDER (1978) for typical stratifications at mid-latitudes that the intermediate baroclinic features are connected with a meridional wave crest of the second mode of very low-frequent Rossby waves. This conclusion is confirmed by the corresponding wave length of about 150 km for vanishing group velocity according to KRAUSS and WUEBBER (1982).

The estimated eddy shifting of about 5 $km.d^{-1}$ yields a "wave length" of about 160 km if the visual period of 16 days is assumed. The accordance of both wave lengths underlines the superposition of local forced dynamics with a time scale of about 16 days on the eddy-like events which are generated in other way within intermediate layers between 100 dbar and 500 dbar. The "wave length" of 150/160 km is well manifested by the observed field distributions in Fig. 6a, b, c, d. The conception of superposition explains too the one phenomenon which is locally fixed at station 361 (411), compared to Fig. 3, because the isotherm of 24 °C is vertically dislocated by the influence of local atmospheric conditions on it.

3.4. Vorticity estimations

The wind stress curl is calculated from the local winds which are shown in Fig. 2. The mapped values of $rot_z\vec{\tau}$ are compared with the topography of the 15 °C isotherm and with the topography of the sea surface relative to the reference level of 1 000 meters in Fig. 6.

The wind stress curl determines the local Ekman pumping by the linear vorticity balance at a f-plane for steady state conditions. The vertical velocity at the Ekman depth D is $w^D = (\hat{\rho}f)^{-1}\ rot_z\vec{\tau}$, where D is the depth with vanishing stress, f is the local Coriolis parameter, $\hat{\rho}$ is the mean density between the sea surface and D, while $\vec{\tau}$ is the vector of wind stress at the sea surface.

From Fig. 6a, it can be seen a belt with downward motions characterized by negative sign of $rot_z\vec{\tau}$. This belt is bounded by two zones with upward Ekman pumping. The general space structure in Fig. 6a is quite in accordance with the horizontal distribution of the intermediate layer in Fig. 6b.

The Ekman pumping produces an additional stretching or shrinking of the water column above the intermediate layers. This effect is demonstrated by the dynamical topography of the sea surface relative to 1 000 meters in Fig. 6d as well as by the layer thickness in Fig. 6b.

For instance, a comparison of the action of relative vorticity produced by winds within the 100 dbar top layer with the relative vorticity produced by currents within the layer between 300 dbar and 600 dbar on vertical structures of isotherms is possible by the observations at station 411 in Fig. 4b, at station 465 in Fig. 6a, b, c, d and in Fig. 8a, b, c.

Station 465 is located near the position 22° N, 27° W. The wind stress curl of about $-10^{-6} N.m^{-3}$ induces a downward motion of about $-2.10^{-5} m.s^{-1}$ at the Ekman depth. The isotherm of 24 °C shows a "valley" at station 465 (or at 411) by a vertical displacement of about 10-20 meters. This downwarping is induced by a wind generated anticyclonic motion. The mean displacement of 15 m together with the vertical velocity of $-2.10^{-5} m.s^{-1}$ yields the local response time of about 9 days for the downward motion.

Because the potential vorticity is nearly conserved within each homogeneous layer, the wind produced stretching of water column between the sea surface and the 24 °C isotherm is indicated by the dislocation of isotherm from the mean level of 70 dbar down to 85 dbar. This increasing thickness produces additional vorticity of about 20 % in respect to the storaged vorticity within this layer.

Other conditions are observed below the level of 100 dbar. A cyclonic motion generates upwarping of isotherms within the layer between 300 dbar and 600 dbar at station 465 (or at station 411 in Fig. 4b). A comparison between the layer thickness of 10 °C isotherm and 15 °C isotherm at stations 465 and 472 (or at stations 411 and 418 in Fig. 4b) shows an

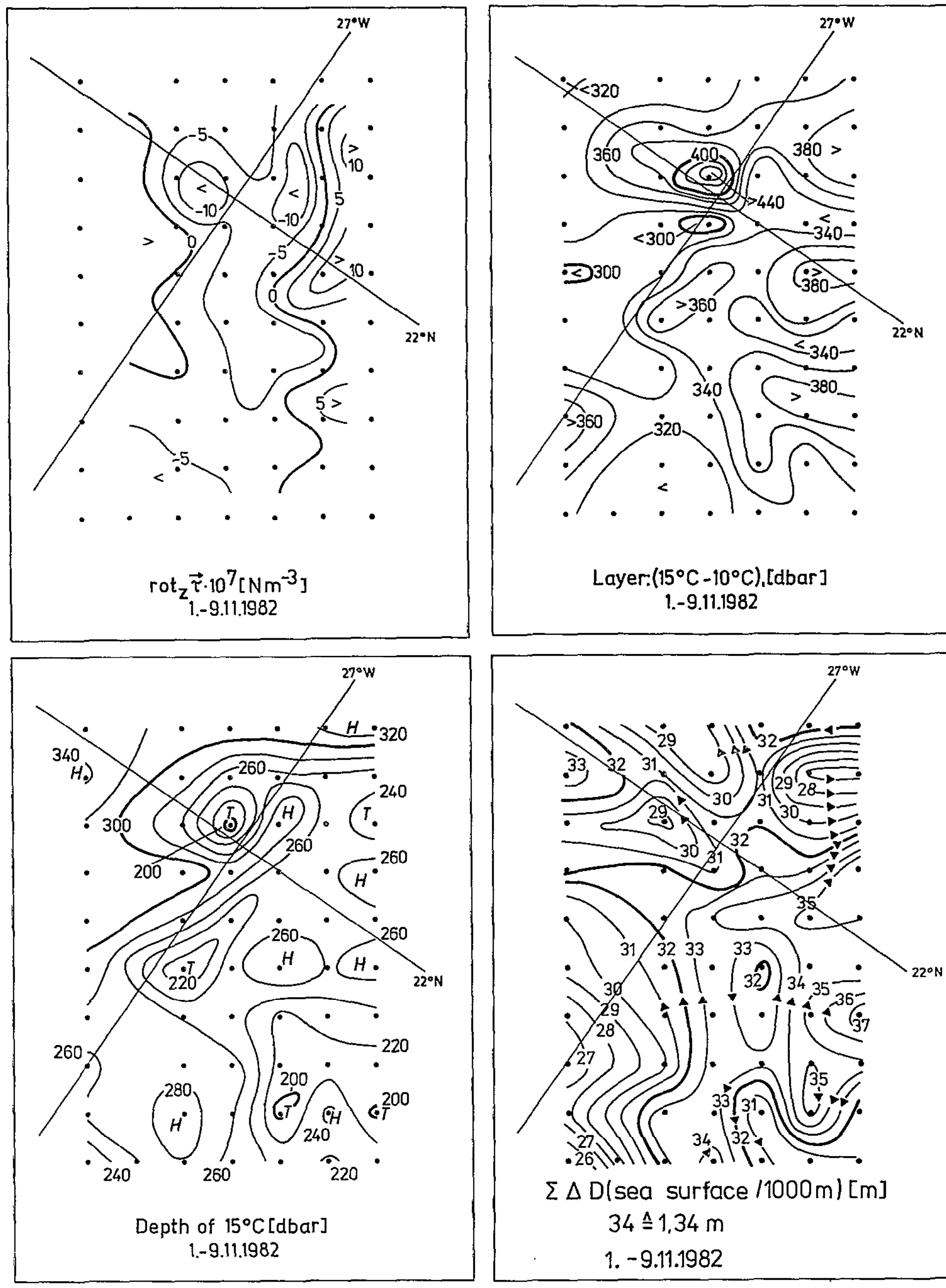

FIG. 6. — Horizontal distributions at the supplement run (cf. Fig. 1) constructed independent of time. (a) Local wind stress vorticity:

$$\mathrm{rot}_z\vec{\tau} = \frac{\tau^y(i+1,j) - \tau^y(i-1,j)}{2\,\Delta x} - \frac{\tau^x(i,j+1) - \tau^x(i,j-1)}{2\,\Delta y}$$

(b) Thickness of water column in dbar between the 15 °C and 10 °C isotherm

(c) Topography of the 15 °C isotherm surface; H denotes high pressure above it while T marks low pressure above it

(d) Topography of the sea surface anomaly relative to the 1 000 m reference level with arrows of geostrophic surface currents (1.34 m correspond to 1.34 dyn.m, the difference of 2 dyn.cm yields a geostrophic velocity of 10 cm^{-1} which is perpendiculary directed to the station distance of 20 nm)

Distribution horizontale sur le réseau de stations supplémentaire (cf. Fig. 1), indépendamment du temps

(a) *Vorticité de la tension du vent local:*

$$rot\vec{\tau}_z = \frac{\tau^y(i+1,j) - \tau^y(i-1,j)}{2\,\Delta x} - \frac{\tau^x(i,j+1) - \tau^x(i,j-1)}{2\,\Delta y}$$

(b) *Hauteur de la colonne d'eau en dbar entre l'isotherme 15 °C et la couche 10 °C*

(c) *Topographie de la surface de l'isotherme 15 °C; les hautes pressions au dessus de cette surface sont notées H, les basses T*

(d) *Topographie dynamique de la surface relative à la profondeur de référence de 1 000 m, avec flèches indiquant les courants géostrophiques de surface*

(1,34 correspond à 1,34 dyn.m; la différence de 2 dyn.cm entre deux stations distantes de 20 nm entraîne une vitesse géostrophique de 10 cm.s^{-1}, perpendiculairement à la ligne joignant les deux stations)

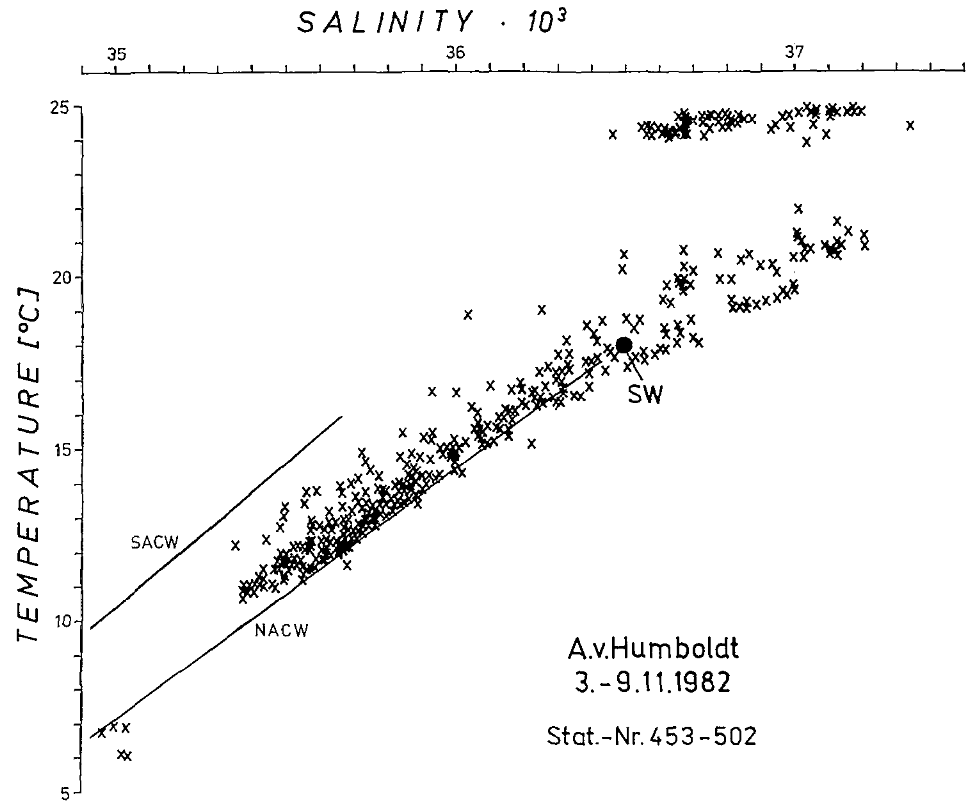

FIG. 7. — Temperature-salinity relationship from selected depths independent of the station during the supplement programme. The determination of salinity was carried out by salinometer measurements declared in the legend of Fig. 1. The lines denote the North Atlantic Central Water (NACW) and the South Atlantic Central Water (SACW) while the point is the T-S centre of Sargasso Water (SW)

Relation température-salinité à des profondeurs choisies, indépendamment des stations, durant le parcours du réseau supplémentaire La détermination de la salinité a été réalisée à l'aide d'un salinomètre. Les lignes figurent l'Eau Nord Atlantique Centrale (NACW) et l'Eau Sud Atlantique Centrale (SACW) ; le point est le centre T.S. de l'Eau des Sargasses (SW)

increasing of relative vorticity of about 40 % at station 465 (or at station 411). From this example, it is to conclude that the local production of vorticity by currents is higher, at least by a factor of two, within the intermediate layer between 300 dbar and 600 dbar than from the local wind stress curl because the curl values do not exceed the amount of 10^{-6}N.m^{-3} at neighbouring stations (cf. Fig. 6a). Caused by these facts, we will interpret the presented observations as a meandering internal front.

3.5. **Water properties**

Oceanic fronts demarcate waters of different hydrographic properties. According to Fig. 7 the influence of SACW on the mixed water is highest within the temperature range between 12 °C and 15 °C, i.e. in depths between the 200 dbar and 500 dbar pressure level, where the isotherms show a rapid upwarding in Fig. 4 and where the strongest horizontal temperature gradients are observed.

The distance of a selected T-S point from the straight lines of central waters is an indirect measure for the mixing processes between NACW and SACW by the assumption of isopycnal mixing (see Fig. 7).

The isopycnal mixing analysis describes the water mass distribution to lowest order correctly, as it was shown by KIRWAN (1983). TOMCZAK (1981) has studied mixing processes between SACW and NACW by an analogical conception along a larger scale frontal zone off Northwest Africa. Fig. 7 indicates that the area under consideration is influenced by the Sargasso Water (SW) within the subsurface layer between 150 dbar and 200 dbar; thus, a hint is given for the connection of this area with subsurface waters from the North Atlantic Current system. This water is situated above the SACW-NACW mixed water.

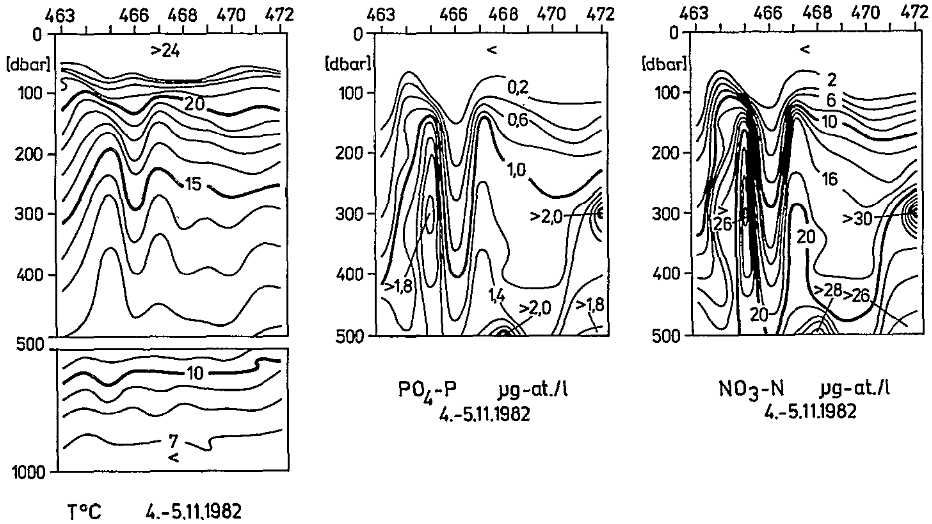

FIG. 8. — Example for a vertical section through an intermediate front north of Cape Verde Islands: (a) temperature, (b) phosphate, (c) nitrate

Exemple de coupe verticale à travers le front intermédiaire au nord des Iles du Cap Vert: (a) *température,* (b) *phosphate,* (c) *nitrate*

On the other hand, intense vertical motions are produced along the internal front by the kinematic boundary condition of vanishing velocity normal to the frontal zone (compare 3.3.) as it is demonstrated, for example, by the vertical nutrient distribution in Fig. 8b, c. It is to note, the vertical displacements of nutrient isolines are essentially stronger, nearly by a factor of three, than the corresponding dislocations of isotherms in layers between 100 dbar and 500 dbar in Fig. 8a.

Furthermore, from Fig. 8 it can be seen that an internal downwelling centre lies in a distance of only 40 km from two neighbouring upwelling regions.

4. CONCLUSIONS

Intermediate eddy-like features were presented from a mesoscale oceanographic station grid placed north-west off Cape Verde Islands during October/ November 1982.

These baroclinic phenomena were coupled on an inner oceanic front zone which demarcates mixed waters with a high degree of South Atlantic Central Water properties from waters with pure conditions of North Atlantic Central Water in the layer between 100 dbar and 500 dbar.

The mapped oceanographic fields generally show a meridional orientation of this meandering demarcation zone. From the used data set and from the literature, it is speculated that the intermediate frontal zone is cut of a meridional wave crest which is formed by the second or third mode of very low frequency Rossby waves. This kind of waves is likely forced by annual and/or semiannual fluctuations of north-east trades. They start from the region of continental slope off Northwest Africa and travel to west. Poleward flowing undercurrents transport waters with SACW properties from lower up to higher latitudes in this nearshore zone. The undercurrents are dynamical part of Rossby waves which are radiated into the open Atlantic by influence of the annual and semi-annual wind forcing of north-east trades. A meridional wave crest will propagate out of the forcing area on its way to west, because the northern boundary of north-east trades is not zonally orientated. Outside the forcing field, other dynamics enter the motions. The wave crests are disturbed along the boundary of forcing area. Increasing baroclinic instabilities extract energy from the field of potential energy in order to generate eddy-like features within intermediate layers. The presented observations show such phenomena on both sides of the climatological position of northern boundary of north-east trades. This atmospheric discontinuity zone meridionally pulsates with a virtual period of about 16 days. This time scale is much to low in order to influence the eddy-like motions directly. However, the local winds determine the current field within the 70 dbar top layer. The area under consideration was influenced by waters from the North Atlantic Current system above the 10 °C isotherm, while it was marked by mixed waters between the North and South Atlantic Central Waters in the layer between the isotherms of 15 °C and of 12 °C.

Caused by this, we can expect a dynamical connection between the equatorial system of subsurface currents and the undercurrent in the area of coastal upwelling, as well as between the upwelling undercurrent off the continental slope and the eddy-like phenomena north-west off Cape Verde Islands.

In order to make a serious assertion on the dynamics of such baroclinic features further continuous investigations are needed to clarify the present confusion of recent conceptions. By this view point the r/v "A.v.Humboldt" will complete the researches in this area in the following years during different seasons.

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