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PHYSICAL AND CHEMICAL ASPECTS OF TRANSIENT STAGES OF THE UPWELLING AT SOUTHWEST OF CABO FRIO (LAT. 23°S - LONG. 42°W)

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Synopsis

An upwelling event was observed during February 1971 in the coastal region between Cabo Frio and Saquarema Point. Isolated upwelled water observed on a first survey, with a temperature of 17°C, oxygen concentration of 4.2 ml/liter and inorganic phosphate concentration of 0.6 μg-at/liter, clearly indicating its subsurface origin, was replaced, after a period of four to seven days, by coastal water with a temperature of 22°C, oxygen concentration of 5.0 ml/liter and inorganic phosphate concentration of less than 0.3 μg-at/liter. The evidence indicates that this replacement took place due to an eastward coastal current with a maximum velocity of nearly 5.0 nautical miles per day. The subsurface distribution of the chemical and physical properties indicates that the upwelling occurred mostly in the narrowest portion of the continental shelf.

Introduction

Upwelling is characterized by ascending motions by which cold and fertile waters from subsurface layers are brought to the surface inducing anomalies in the distribution of oceanographic properties. The ascending motions in open sea, as inferred from the continuity equation, result from the divergence of the velocity field at the surface layer; near the continents, upwelling can be generated by a one-sided divergence due to wind drift currents. General explanations of the phenomenon in coastal regions, applying Ekman's (1905) theory of the wind drift currents, were made by Thorade and McEwen in 1909 and 1912, respectively (Sverdrup, 1938).

Along the western coastal regions the upwelling phenomenon is particularly remarkable; examples of these regions are found in the coasts of Africa, Chile, Peru and part of California. However, upwelling can also occur in eastern coastal regions and has been observed by Emílsson (1959, 1961), Silva (1957, 1968) and Mascarenhas, Miranda & Rock (1971) along the coast of Cabo Frio (Brazil).

Surface water renewal by upwelling makes high nutrient concentration available in the euphotic zone. This fact has an important effect on the marine biological environment recognized by several authors (Gunther, 1936; Posner, 1957; Hart & Currie, 1960 and many others).

The transient phases of upwelling have been rarely observed. A detailed analysis of the early stage of an upwelling event off the Oregon coast (USA), as a result of standard hydrographic observations along a vertical section, has been made by Smith *et al.* (1966).

Recently, observations on stages of upwelling along the coast between Cabo Frio and Guanabara Bay by means of continuous surface temperature and salinity measurements, were presented by Ikeda, Miranda & Rock (1971) and Ikeda (1976).

The vertical distribution of temperature and salinity during upwelling induced by the wind has been studied by Silva & Rodrigues (1966).

An oceanographic cruise along the coast of Rio de Janeiro (Fig. 1), was

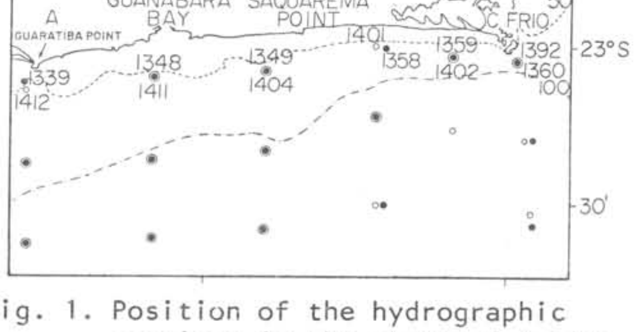

Fig. 1. Position of the hydrographic stations in the observed region. First survey (from 4 to 6 February 1971) and second survey (from 10 to 13 February 1971) stations are shown as solid circles and blank circles, respectively.

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undertaken in February 1971 by the research vessel "Prof. W. Besnard" with the purpose of reporting the upwelling features in the Cabo Frio region. The oceanographic properties discussed in this paper were measured during the periods extending from the 4th through the 6th and from the 10th through the 13rd of February 1971. During this time interval, the upwelling in the coastal region to the west of Cabo Frio was obscured by an influx of warm, nutrient-poor water coming from the east along the coast.

Methods and units

The water samples were taken with standard Nansen casts. The temperature (°C) was measured with reversing thermometers and the salinity (°/₀₀) was estimated with an inductive salinometer (Beckman, model RS-7B); the conductivity ratios (R_t) were converted to salinity utilizing the International Oceanographic Tables (Joint Panel on Oceanographic Tables and Standards, 1966).

The determination of the dissolved oxygen (ml/l) was made using the modified Winkler method and the relative oxygen (%) computed according to Truesdale & Gameson (1957).

Inorganic phosphate (µg-at PO_4 - P/l) determinations were made using the phosphomolybdate complex with ascorbic acid, in frozen samples.

Results and discussion

Physical and chemical structure at the surface

Temperature - The temperature variations due to advective processes are clearly shown in Figure 2. In the first survey (A), an abnormal variation, ranging from 27°C (southwest of Guanabara Bay) to 17°C (20 nautical miles to the west of Cabo Frio), was observed; the presence of this minimum probably occurred due to the vertical advection of waters from deeper layers (upwelling). In the second survey (B), the temperature distribution was completely modified; the 17°C surface water located between Saquarema Point and Cabo Frio, was replaced by warmer water (21-23°C) and the temperature minimum seemed to be shifted to the east near Cabo Frio.

This great temperature change in the coastal region could not be the result of local processes of air-sea energy exchange (as we will discuss later in this paper) and the isotherm configuration seems to indicate advection of warm waters caused by an eastward current.

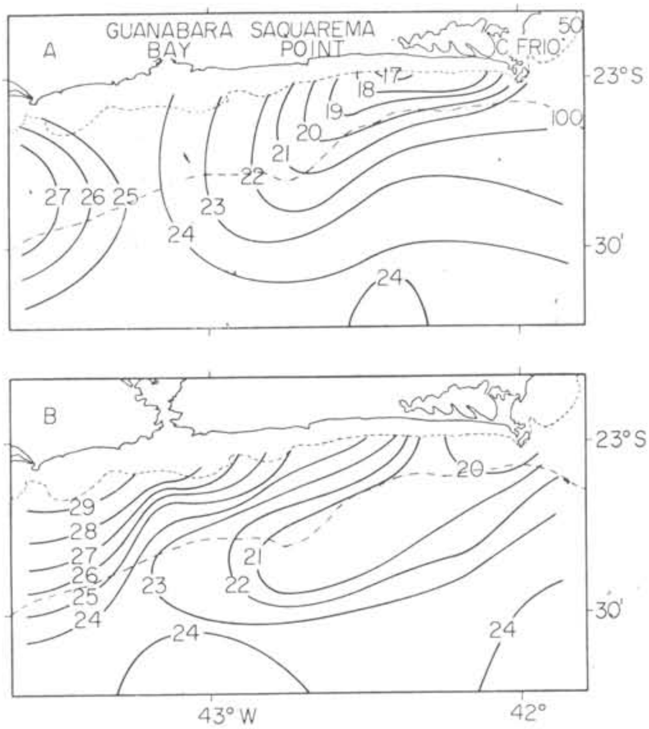

Fig. 2. Surface temperature (°C).
A - First survey
B - Second survey

Salinity - In both observations (Fig. 3), the salinity variation was within 35.2 and 36.2°/₀₀. The salinity minimum during the first survey (A) was located to the south of Guanabara Bay; this minimum can be attributed to less saline residual waters from the bay, since the station near this region was taken during the flood tide. The salinity maximum observed to the south of Cabo Frio (S > 36.0°/₀₀) was associated with a temperature higher than 20°C, indicating that these coastal waters had a Tropical origin. However, the cold water salinity range was 35.6 - 35.7°/₀₀, which indicates the presence of Subtropical waters.

Even though the extreme salinity variations in both observations were the same, aspects of the horizontal distribution of salinity differ. The meandering patterns in the first survey (Fig. 3*a*) pointed out instabilities in the cyclonic shear region of the Brazil Current, where the upwelled Sub-Tropical waters interact with Tropical waters (S > 36.0°/₀₀) transported southwards by the Brazil Current. This type of

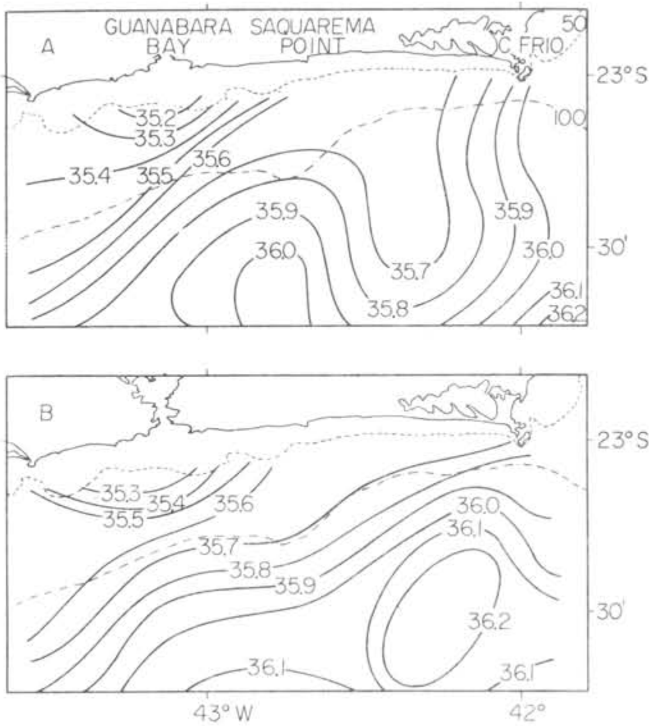

Fig. 3. Surface salinity (°/₀₀).
A - First survey
B - Second survey

instability was observed in other upwelling regions and can be explained by the wind force and direction changes (Sverdrup, 1938).

In the second survey (Fig. 3*b*) the isohalines are no longer meandering but rather uniform. This configuration suggests, as does the thermal distribution, a nearshore current flowing eastward. The core with salinity greater than 36.2°/₀₀, to the south of Cabo Frio, seems to be an eddy originated from the meander degeneration of the Brazil Current.

The steady salinity minimum (S < 35.3°/₀₀) to the south of Guanabara Bay, also observed during the flood tide, confirms the influence of the residual and less saline waters coming from the Bay.

Inorganic phosphate and oxygen - The inorganic phosphate and oxygen concentrations on the surface are shown in Figures 4 and 5, respectively. A comparison of Figures 2*a*, 4*a* and 5*a* for the first survey shows that the region where the maximum inorganic phosphate concentration (0.6 µg-at PO_4 - P/1) appears is coincident with the temperature (17°C) and oxygen (4.2 ml/1) minima. This evidence suggests that the anomalies were produced by upwelled water masses of *Subtropical origin*.

Regarding the dissolved oxygen, besides the minimum of 4.2 ml/1 which appears in the coastal region to the west of Cabo Frio, another one of low value (4.4 ml/1 or 95%) to the south of

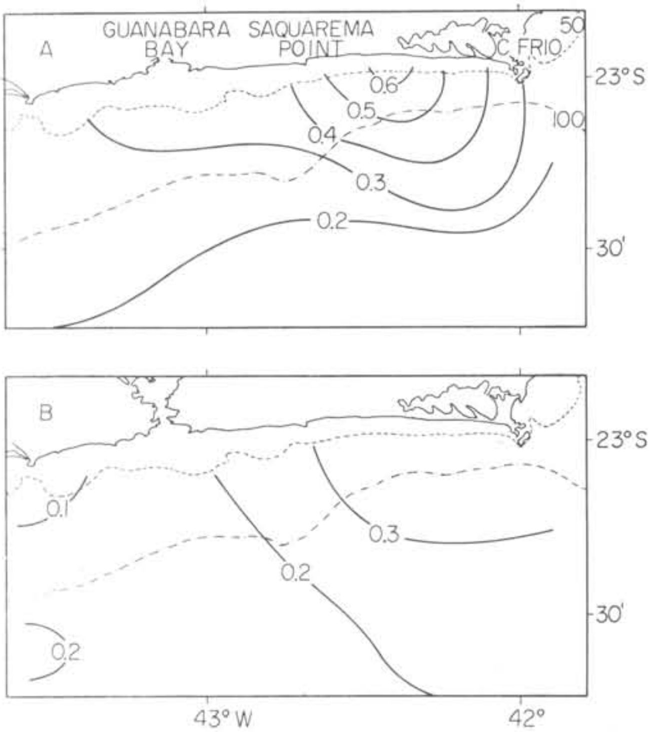

Fig. 4. Surface inorganic phosphate concentration (µg-atPO_4-P/l).
A - First survey
B - Second survey

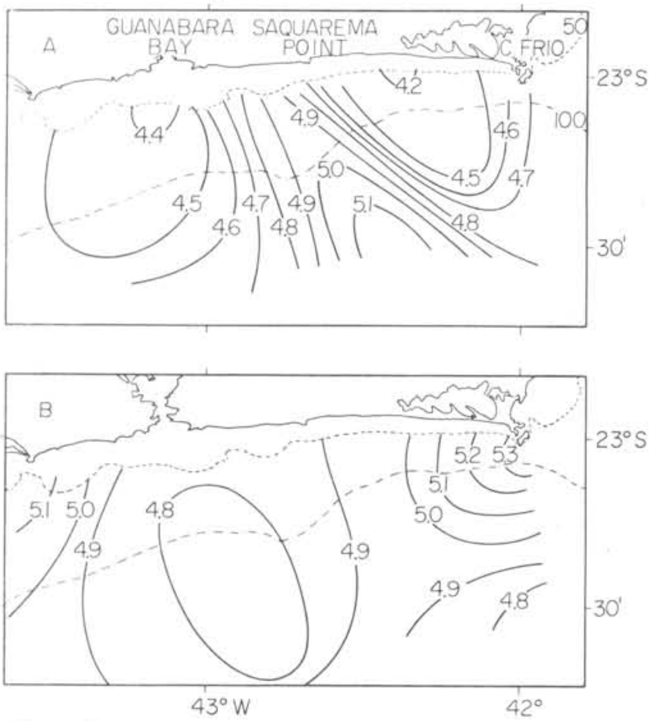

Fig. 5. Surface oxygen concentration (ml/l).
A - First survey
B - Second survey

Guanabara Bay and associated with the salinity minimum previously described, was found.

In the second survey, the surface distribution of the inorganic phosphate and oxygen concentrations (Figs 4*b* and 5*b*) have been submitted to strong variations. The decrease in the concentration of the first property in the coastal region to the west of Cabo Frio, associated with the increase in the temperature and oxygen concentration, indicates that its change is not only due to advection and diffusion processes, but also due to a certain biological consumption.

Physical and chemical structure at 10m depth

Temperature - For the first survey the nearshore water temperature ranged between 17°C and 23°C (Fig. 6*a*). The temperature minimum (17°C) extended from Cabo Frio to Guanabara Bay, comprising a larger area than at the surface. In the second survey (Fig. 6*b*) the temperature minimum had a small area of influence and the rise of temperature in the nearshore region, to the west of Guanabara Bay, suggests a coastal current flowing to the east, as was noticed in the surface distribution.

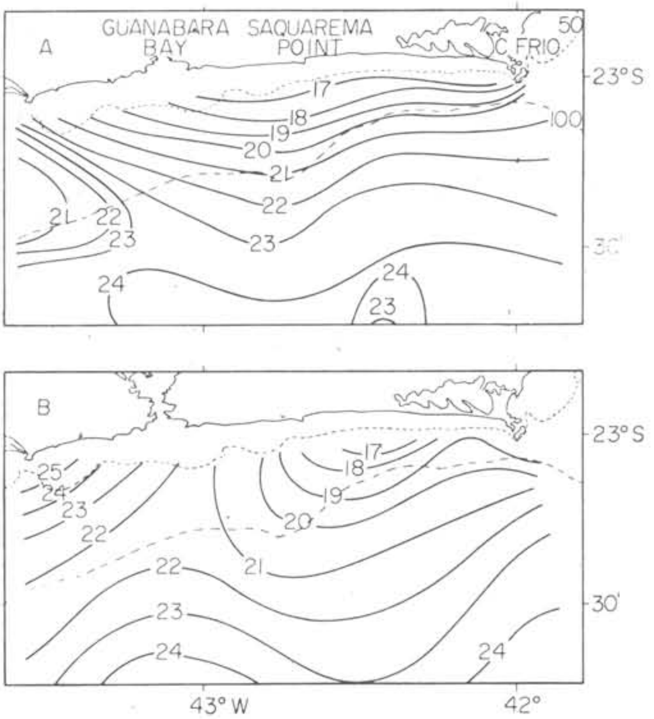

Fig. 6. Temperature (°C) distribution at 10 m depth.
A - First survey
B - Second survey

Salinity - In the nearshore region, the salinity range was within 35.6°/₀₀ and 36.0°/₀₀; the minimum occurred to the south of Saquarema Point and the maximum to the south of Cabo Frio. The isohalines (Fig. 7*a*) show some similarity with the surface distribution, except for the region to the south of Guanabara Bay where the less saline waters (S < 35.6°/₀₀) were absent at this depth.

During the second survey (Fig. 7*b*), the salinity of the coastal waters had a maximum increase of 0.2°/₀₀; the salinity minimum (S ≃ 35.7°/₀₀) was located in the vicinity of Cabo Frio. Its eastward displacement compared with the first survey, and the observed change in the isohalines, has confirmed the presence of the coastal current.

The comparison of the temperature and salinity structures discussed above, shows that at this depth the coastal region is more influenced by Subtropical waters.

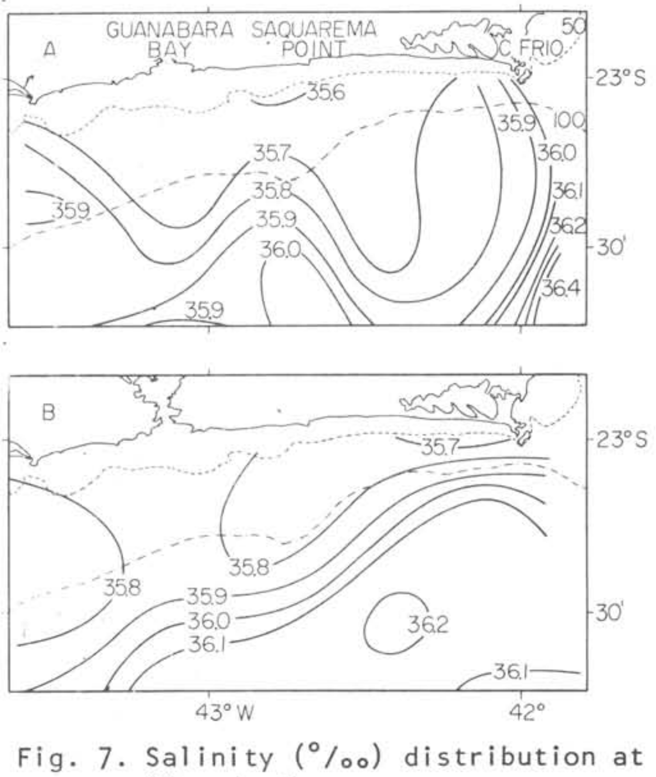

Fig. 7. Salinity (°/₀₀) distribution at 10 m depth.
A - First survey
B - Second survey

Inorganic phosphate and oxygen - The configurations of the inorganic phosphate (Fig. 8*a*) and oxygen concentrations (Fig. 9*a*) are similar to the surface distributions in both surveys and show that the process which modifies the inorganic phosphate concentration extends at least to 10 m depth (Fig. 8*b*).

However, for the second survey, the

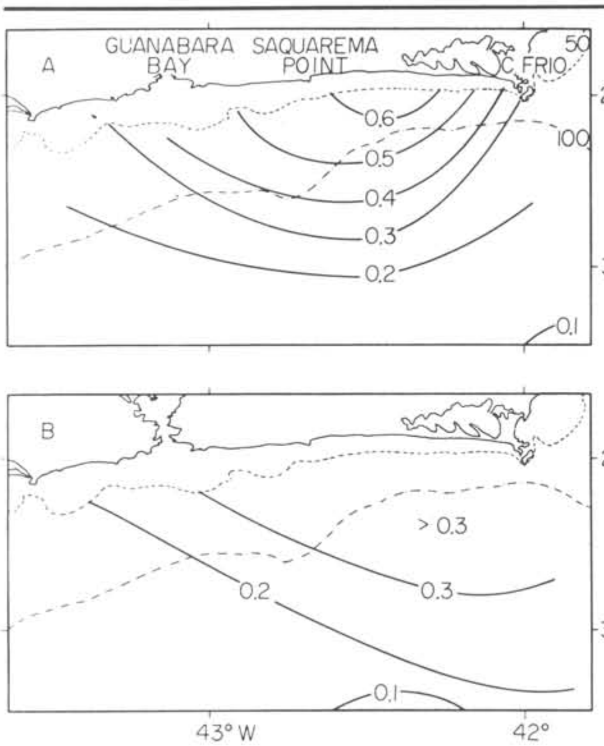

Fig. 8. Inorganic phosphate concentration (µg-at PO_4 - P/l) at 10 m depth.
A - First survey
B - Second survey

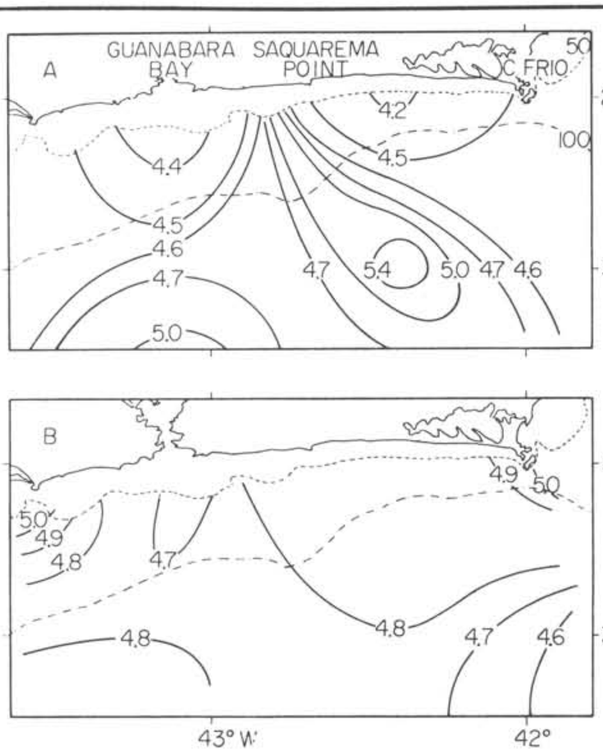

Fig. 9. Oxygen concentration (ml/l) at 10 m depth.
A - First survey
B - Second survey

oxygen distribution (Fig. 9*b*) shows smaller values than those obtained at the surface, probably due to the physical processes already described. It is worth mentioning that between stations 1358 (first survey) and 1401 (second survey) the production of oxygen is reflected directly in the inorganic phosphate depletion.

Physical and Chemical Structure at 25 m depth

Temperature and salinity - The temperature rise in the coastal region was less than 1°C. Thus, it follows that the influence of the warm eastward coastal current was less at this depth. In both surveys the temperature minimum (T ≃ 16°C) was very close to the Cape.

The range of the salinity variation was 1°/oo, with the minimum of 35.6°/oo in the coastal region and a maximum of 36.6°/oo in oceanic waters to the south of Cabo Frio. In both surveys, the isohalines less than 36.2°/oo showed a meandering configuration, probably as a result of the Brazil Current fluctuations.

At this depth, the influence of the SubTropical water over the continental shelf predominates.

Inorganic phosphate and oxygen - During the first survey the maximum in the inorganic phosphate concentration, slightly higher than 0.9 µg-at PO_4 - P/l, was located in the region to the south of Guanabara Bay. The concentration of this property decreases southward almost uniformly, and the values less than 0.4 µg-at PO_4 - P/l were associated with Tropical water. The oxygen concentration structure has two minima (O_2 ≃ 4.2 ml/l) near the coast. The minima were associated with the highest values of inorganic phosphate concentration.

In the second survey, the maximum of 0.6 µg-at PO_4 - P/l in the inorganic phosphate concentration was located in the region between Saquarema Point and Cabo Frio. To the west of this point, a decrease in the concentration of the inorganic phosphate was associated with an increase in the oxygen concentration.

Physical and chemical structure at 50 m depth

Temperature and salinity - During both surveys, the distribution of temperature and salinity along the coast showed minimum values of ≃ 15°C and ≃ 35.6°/oo, respectively. The offshore increase of these properties was indicated by the isoline configurations, which show an almost uniform pattern. However, some changes in the patterns between surveys have been noticed, which are probably due to the meandering of the Brazil Current.

Inorganic phosphate and oxygen - The inorganic phosphate distributions showed, for the first survey, two maxima (both of 0.9 µg-at PO_4 - P/1) located in the coastal region to the west of Cabo Frio and to the south of Guanabara Bay. The maxima were associated with minimum values of the oxygen concentration (3.8 and 4.0 ml/1, respectively). According to the classification of bottom water masses given by Mascarenhas *et al.* (1971, p.300), these extreme values are associated with the Subtropical Shelf Water (STSW), as can be verified by the TS Diagram.

During the second survey, a slight decrease in the inorganic phosphate concentration in the coastal region to the east of Guanabara Bay was noticed. To the west of this bay, a maximum of 1.4 µg-at PO_4 - P/1 associated with a value of oxygen concentration of ≃ 4.7 ml/1 appeared. Due to this association, this maximum does not seem to be real, and probably was a result of the contamination of the water sample by bottom sediments.

Physical and chemical structure at 100 m depth

A comparison of the distributions of the physical and chemical properties at 100 m depth shows the following common characteristics (Figs 10-13):

a - Sub-Tropical Shelf Waters (STSW) and Sub-Tropical waters (STW) are predominant.

b - The temperature (13°C < T < 16°C), salinity (35.4°/₀₀ < S < 35.6°/₀₀) and oxygen (4.0 ml/1 < O_2 < 4.4 ml/1) minima which are associated with the maximum inorganic phosphate concentration (> 0.7 µg-at PO_4 - P/1), were located in the region to the south of Cabo Frio. These characteristics in the distribution of the physical and chemical properties show conclusively that in this region, where the continental shelf is very narrow, the influences of the deep water through ascending motions and/or vertical mixing processes is more intense.

The Brazil Current advective influence, transporting water from the east to the west, is demonstrated by the isoline configuration of the second survey (Figs 10*b* through 13*b*), particularly by the temperature and salinity distributions. The presence of the upwelled water mass indicators (temperature and oxygen minima associated with the maximum in the inorganic phosphate concentration) on the surface, to the west of Cabo Frio, may also be due to the advective influence of the Brazil Current.

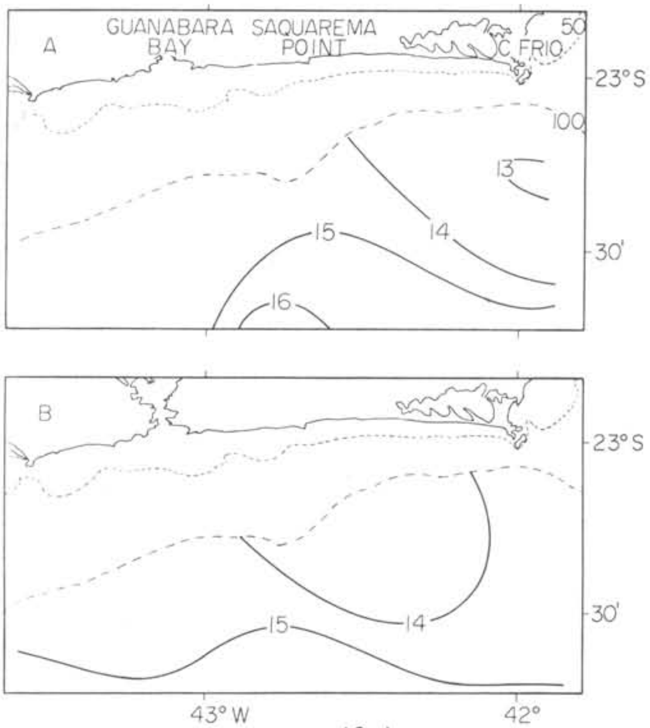

Fig. 10. Temperature (°C) distribution at 10 m depth. A - First survey; B - Second survey

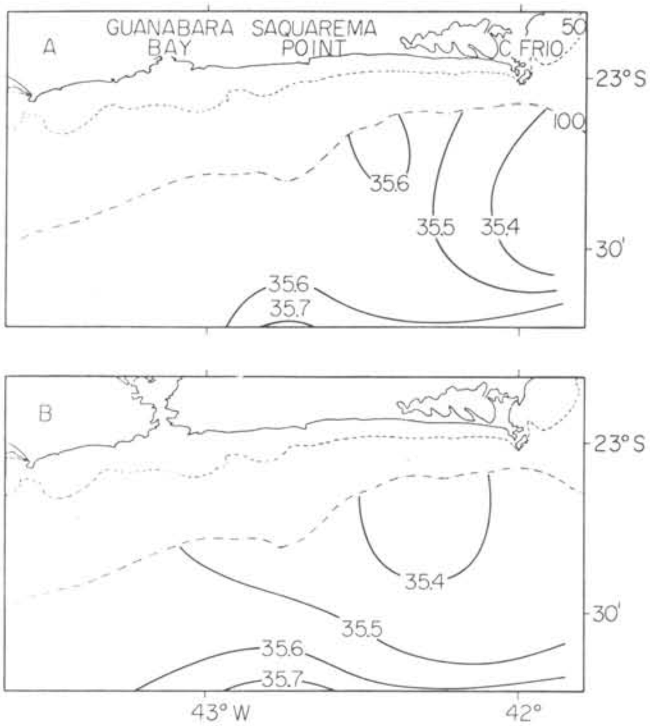

Fig. 11. Salinity (°/₀₀) distribution at 100 m depth.
A - First survey
B - Second survey

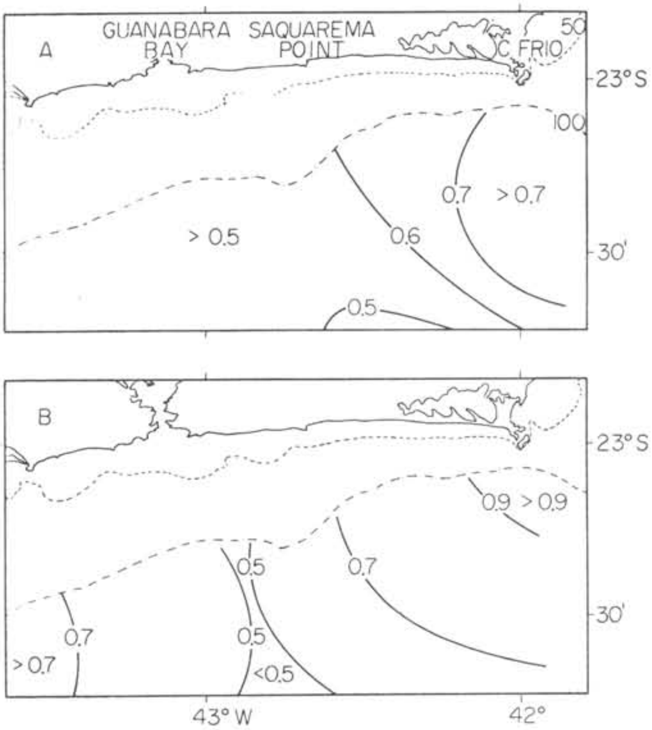

Fig. 12. Inorganic phosphate concentration (µg-at PO_4-P/l) at 100 m depth.
A - First survey
B - Second survey

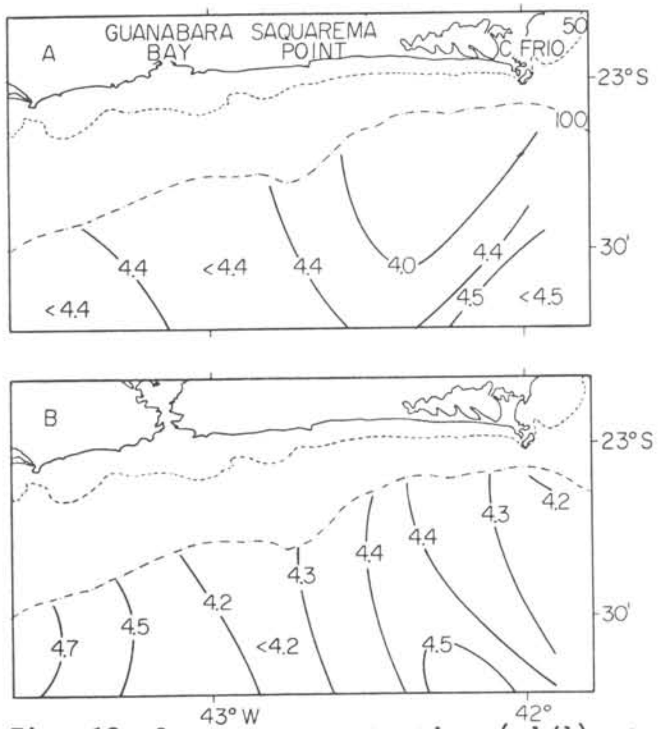

Fig. 13. Oxygen concentration (ml/l) at 100 m depth.
A - First survey
B - Second survey

The baroclinic adjustment of the density field, associated with variation of the geostropic flow of the Brazil Current, is suggested by the fluctuations of the cold and less saline waters withdrawing from the coast. This phenomenom may also transport cold and fertile waters upon the continental shelf and so, effects similar to those produced by upwelling may occur in the surface layers (Defant, 1961 - p.645); these two processes are indistinguishable in their influences.

The horizontal advective process as deduced by an approximate heat budget analysis

In the previous discussion of the horizontal distributions of temperature and salinity in the upper layers an eastward flow of warm coastal water was suggested; it can be shown by an approximate heat budget analysis, that the change in the surface thermal structure in the coastal region (Fig. 2) was mainly due to an horizontal advective process.

Table I presents the differences in vertically integrated heat storage (ΔQ) per unit area (cm^2) and unit time (day), resulting from the variations in the vertical thermal structure in the upper 10 m layer along the coast (Fig. 1). These approximate values were obtained by vertical integration, in accordance with Stommel & Fedorov (1967). The time rate differences were calculated taking into account the time interval between successives observations (4.4 to 8.3 days).

These differences, are the result of the combined action of the local climatic processes (solar radiation, back radiation, solar radiation reflection, heat loss by evaporation and heat gain or loss due to the interchange with the atmosphere), advection and turbulent diffusion.

During February 10 and 11 the mean value of the total solar radiation, recorded at the Research Station of Ubatuba (Fig. 14), was 423.0 cal. cm^{-2}. day^{-1}. This information was made available to us by Dr. Clovis Teixeira (personal communication). From the results of Privett (1960) we may estimate, for the summer months, that less than 30% of the global solar radiation incident on the sea surface is absorved and transformed into sensible heat on the sea surface (most of the solar radiation energy reaching the sea surface is mainly lost due to reflection, back radiation and evaporation). Even though errors in the extrapolation of the solar radiation reaching Ubatuba to the region of Cabo Frio are perfectly possible to exist, it is possible to infer that the heat gain indicated in

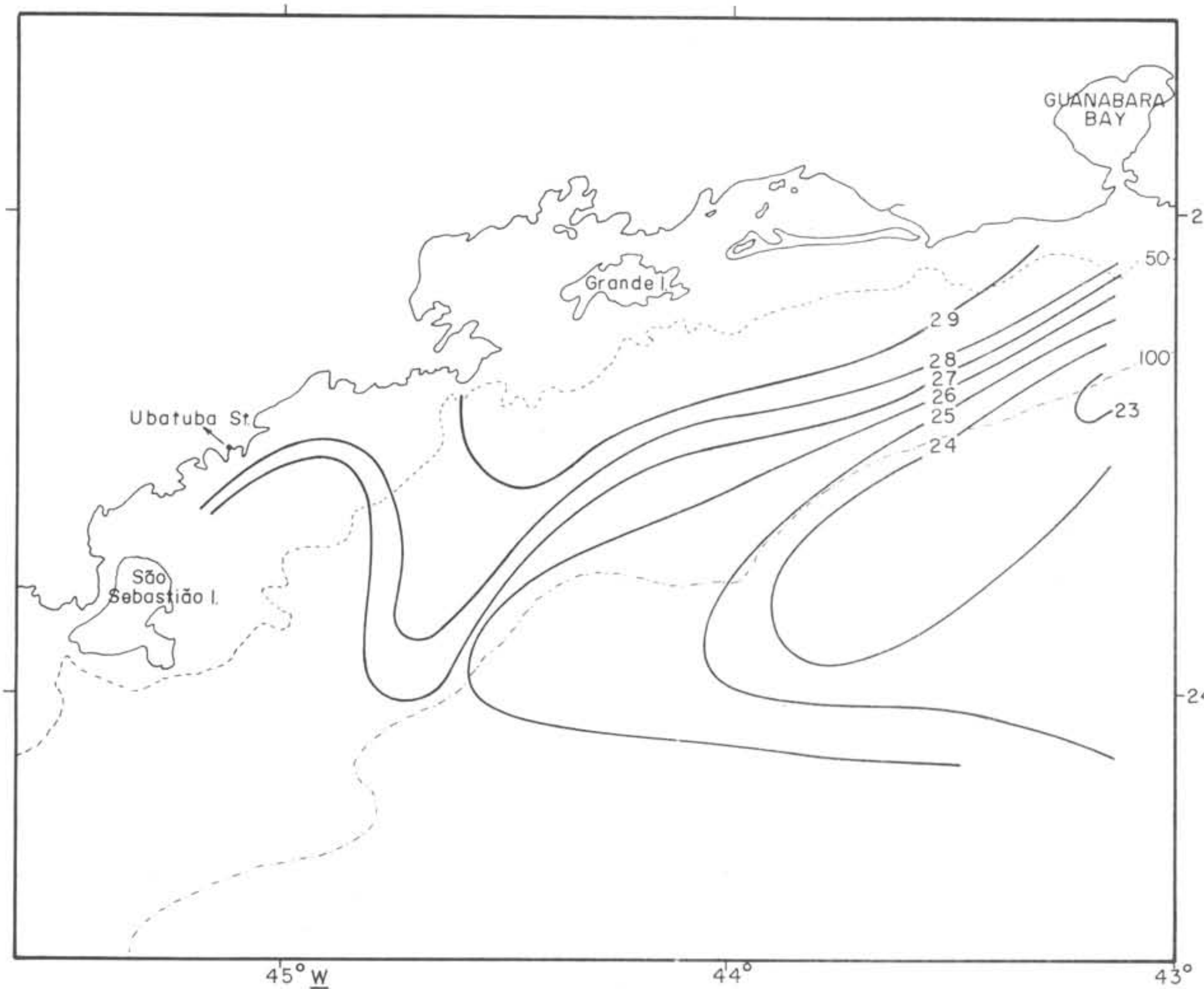

Fig. 14. Surface temperature (°C) distribution off Ilha Grande Bay.

Table I has been mainly due to the advection of warm coastal water. In the same way the heat loss of 436,0 $cal.cm^{-2}.day^{-1}$ observed to the south Cabo Frio (St. 1392 - 1360), which seems to be an anomaly, may also be explained as an advective influence of the cold upwelled waters. In fact, the eastward displacement of the temperature minimum on the surface layer was previously discussed when the temperature distribution was analysed.

The surface temperature distribution off Ilha Grande Bay (Fig. 14) shows that this bay may be the main source of the warm water, which could be able to influence the temperature of the coastal region vicinity. The waters of the inner region are warmed up during the summer and its influence is observed in the coastal region due to the surface outflow. The core of colder water (23°C) southeast of Ilha Grande clearly indicates the influence of the cold upwelled water masses.

Table I - Time rate differences in the heat storage ($cal.cm^{-2}.day^{-1}$) in the stations along the coast

St.	1412-1339	1411-1348	1404-1349	1401-1359	1402-1359	1392-1360
ΔQ	404.0	571.0	552.0	667.0	471.0	-436.0

Due to the rapid change in the temperature distribution in the upper 10 m layer, an attempt was made to estimate the zonal component of the warm coastal current. For this purpose the time variation in the zonal displacement of the isotherms was analysed in some detail. If the assumption is made that no heat or water mass was transported across isotherms, the area swept by a given isotherm per unit of time, can then be interpretated as the transport per unit of depth. The computation was done for strips parallel to the coast 5 nm wide, and the results of the coastal current (zonal component) in nm. day^{-1} are given by the isotachs shown in Fig. 15*a*.

The eastward flow was contrary to

the prevailing wind direction (Fig. 15*b*) and appears to originate as a compensation flow due to divergence in the coastal zone. The occurrence of a

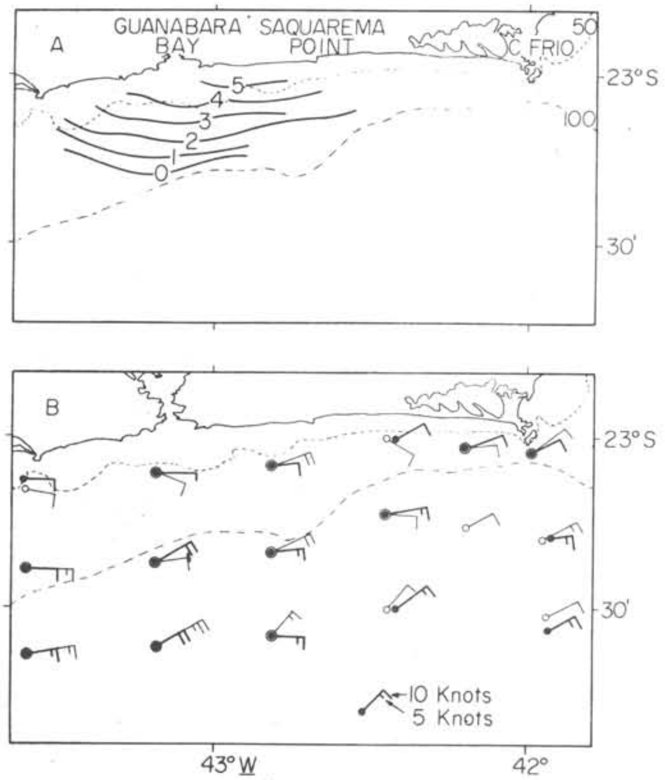

Fig. 15. Isotachs of the eastward estimated flow in nm/day. Wind observations during the hydrographic stations (First survey and second survey observations are shown as solid and blank circles, respectively).

surface countercurrent moving upwind was also detected by Ikeda *et al.* (1971) when describing early stages of upwelling in the same region.

During the same cruise a drift bottle experiment (with a recovery efficiency of 1.5%) was conducted. The results were reported in a personal communication by Mrs. Ellen F. Luedemann which, based on the release and recovery positions and the time interval between them, came up with idealized trajectories and mean velocities ranging from ≃1.0 to ≃3.0 nm/day. These results, shown in Fig. 16, gave a further evidence of the eastward coastal current.

Conclusions

It was observed during this experiment that a cold core (~17°C), relatives low dissolved oxygen (~4.2 ml/l) and high inorganic phosphate concentration (0.6 µg-at PO_4-P/l), initially present in the surface coastal water between Saquarema Point and Cabo Frio and clearly resulting from the upwelled water masses, have been replaced in a few subsequent days by an inflow of warm, nutrient-poor water coming from the east along the coast.

The presence of this coastal flow, which obscured the influences of the upwelled water masses has been confirmed by an approximate heat budget analysis and by drift bottle results. The absolute values reported in this paper should be taken with care and we recommend further direct measurements for more reliable quantitative results.

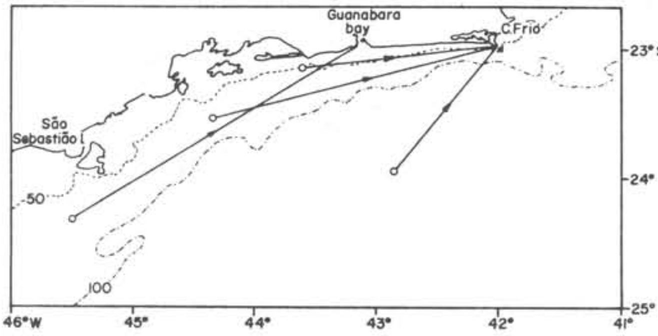

Fig. 16. Idealized trajectories of the drift bottle experiment. Blank circles indicate the release positions.

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Resumo

As observações oceanográficas realizadas em fevereiro de 1971, na plataforma continental entre Cabo Frio e a Ponta de Guaratiba, mostraram a presença e a atenuação de efeitos do fenômeno de ressurgência observados na superfície. A análise detalhada da distribuição térmica na camada superficial evidencia que o processo físico responsável pela atenuação desse fenômeno foi a advecção de uma corrente costeira de águas quentes, fluindo para leste. A componente zonal dessa corrente costeira atingiu nas proximidades da costa o valor máximo de 5 mn. dia^{-1} e a sua intensidade decresceu com o aumento da distância à costa, anulando-se aproximadamente sobre a isóbata de 100 m.

Os efeitos do fenômeno de ressurgência na superfície, observados ao largo da Ponta de Saquarema, eram claramente indicados pelos mínimos de temperatura (17°C) e da concentração de oxigênio dissolvido (4,2 ml/l) bem como pelo máximo na concentração de fosfato (0,6 µg-at/l), que são característicos de águas mais profundas. No intervalo de tempo (4-7 dias) decorrido entre as observações, verificou-se não somente aumentos de temperatura e do oxigênio dissolvido, como também um decréscimo na concentração de fosfatos de aproximadamente 50% de seu valor inicial.

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