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RATE OF WATER RENEWAL AND PHOSPHATE INPUT IN THE GULF OF CARIACO, VENEZUELA

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ABSTRACT: Hydrographic and chemical conditions in the Gulf of Cariaco are influenced mainly by variations in upwelling, which are intimately associated with the wind regime. Displacement of water in the gulf is primarily controlled by prevailing winds from the E-NE direction, which enhance the outflow of surface waters and the inflow of the denser upwelled waters. Although seasonal variations of salinity in the gulf are relatively small, water temperatures fluctuate considerably with the change in the inflow rate of the upwelled subsurface waters. Using weekly water temperature and phosphate concentration data collected during 1974 and 1975, the rate of water renewal and phosphate input into the gulf were determined by setting up a simple model. Is was found that the flush rate varies seasonally with the wind regime. Flushing was completed in approximately 21 days in February 1974, which was the shortest lapse (period of strong winds) and 111 days from June through October 1975, which was the longest lapse (period of weak winds). The influx of external water was estimated to be 245 x 10^9 m^3 in 1974 and 188 x 10^9 m^3 in 1975. Such influx corresponds roughly to 8 and 6 times as much as the whole volume of the gulf. The annual input of phosphate phosphorus was estimated to be about 3,350 tons in 1974 and 2,510 tons in 1975.

RESUMEN: Las condiciones hidrográficas y químicas del Golfo de Cariaco están influidas principalmente por las variaciones de la surgencia la cual está íntimamente relacionada con el régimen de los vientos. El desplazamiento del agua en el golfo está controlado primeramente por los vientos prevalecientes en la dirección E-NE que activa el intercambio de las aguas entre el golfo y el exterior; el flujo hacia el exterior es de las aguas superficiales del golfo y hacia el interior es de las aguas densas surgidas desde el exterior. Las variaciones estacionales de la salinidad en el golfo son relativamente pequeñas, mientras que la temperatura del agua fluctúa considerablemente con el cambio en la tasa del influjo de las aguas subsuperficiales surgidas. Utilizando los datos de la temperatura del agua y de la concentración de los fosfatos obtenidos durante 1974 y 1975, la tasa de renovación del agua e introducción de fosfato al golfo fue determinada por un simple modelo aquí propuesto. Se observó que la tasa de renovación varía estacionalmente con el régimen del viento. La renovación del volumen total del agua se completó aproximadamente en 21 días durante el mes de febrero de 1974, que fue el lapso más corto (período de vientos fuertes) y 111 días desde junio hasta octubre de 1975 que fue el lapso más largo (período de vientos débiles). El influjo de agua externa fue estimado en 245 x 10^9 m^3 en 1974 y 188 x 10^9 m^3 en 1975. Tales influjos corresonden aproximadamente a 8 y 6 veces del volumen total del golfo. La introducción anual de fosfato fue estimada en aproximadamente 3.350 toneladas en 1974 y 2.510 toneladas en 1975.

INTRODUCTION

Several previous workers (RICHARDS 1960; GADE 1961a, 1961b; KATO 1961; GRIFFITHS & SIMPSON 1967; SIMPSON & GRIFFITHS 1967; OKUDA *et al* 1978a, 1978b; OKUDA 1981) have studied and illustrated the hydrographic and chemical characteristics of the Gulf of Cariaco which are influenced by variations in upwelling associated with the wind regime. Topographic and geological conditions of the gulf have also been studied by ROA MORALES & OTTMANN (1961).

A geomorphological characteristic of the Gulf of Cariaco (Fig. 1) is that it is a semi enclosed basin which is connected to the Cariaco Basin through a narrow mouth in the western part. The gulf has a depression

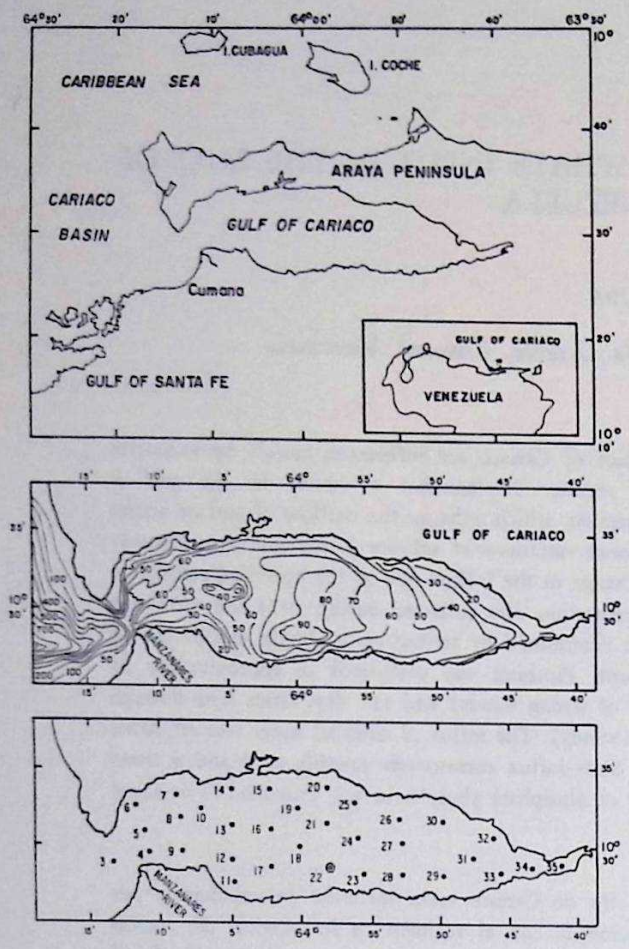


Fig. 1. Map of the Gulf of Cariaco showing 33 hydrochemical stations and bathymetric contours in meters. Weekly observations were carried out in Sta. Nº 22.

(about 90m deep) in the south-central part, that is deeper than the mouth of the gulf (60 - 70m). The Gulf of Cariaco has climatic characteristics of an arid región, where evaporation far exceeds precipitation (8—11 times per year). The effect of river runoff on the hydrochemical conditions in the gulf seems to be of little significance due to the fact that waters discharged from the Manzanares river may be shifted to a surface drift towards northwest (outwards the gulf) by prevailing winds from a E-NE direction. Some small streams also drain into the gulf but with no appreciable amount to affect the hydrochemical conditions.

For lack of appreciable tidal currents, the water exchange in and out of the gulf depends mainly upon wind-driven circulation. Prevailing winds from the E-NE generate the outflow of surface water and the inflow of sub-surface water from the Cariaco Basin into the intermediate and deeper layers of the gulf.

A high primary productivity in the gulf was reported by several previous researchers (RICHARDS 1960; CURL 1960; KATO 1961; HAMMER 1967; FERRAZ DE REYES 1977; MANDELLI & FERRAZ DE REYES 1982) who attributed it to intense upwelling in the region. From an analysis of phosphate balance in the gulf, OKUDA (1981) interpreted that the inflow of the sub-surface waters of the Cariaco Basin into the gulf may contribute to the nutrient enrichment of the upper layers, which tend to lose nutrients by photosynthetic activity, and the upper layers of the gulf appear to receive a continuous supply of nutrients from the Cariaco Basin even during the period of weak wind intensity (OKUDA 1981). On the other hand, GADE (1961b) pointed out that when strong easterly winds become weak, compensating currents will set in, because of the usually sloping density surface with a pressure field balanced against the wind stress. On the basis salinity and temperature date, the same author suggested the existence of a horizontal exchange, without implying vertical circulation, and the frequent occurrences of such reverse currents.

It may be pointed out here that in order to evaluate critically the fertility of the Gulf of Cariaco, it is extremly important to assess the influx rates of external water and nutrients into the gulf. In the present paper, therefore, an attempt is made to estimate these two aspects (*i. e.* rates of water renewal and phosphate input) by applying a simple model, on the basis of weekly variations of temperature and phosphate concentrations in the water column that were observed during 1974-1975.

SOME FEATURES OF METEOROLOGIC AND HYDROCHEMICAL CONDITIONS

On the basis of data compiled by the Meteorological Station, Instituto Oceanografico, Universidad de Oriente, for 1972-1975, OKUDA *et al.* (1978a) and OKUDA (1981) reviewed meteorological conditions for the area of the Gulf of Cariaco, which may be briefly summarized as follows:

The maximum and minimum values of air temperature were found to be 32.2°C and 21.0°C respectively with two distinct periods, *i, e,* slightly lower temperatures from December to March and relatively higher temperatures from April to November. The annual precipitation ranged from 221 mm (1972) to 346 mm

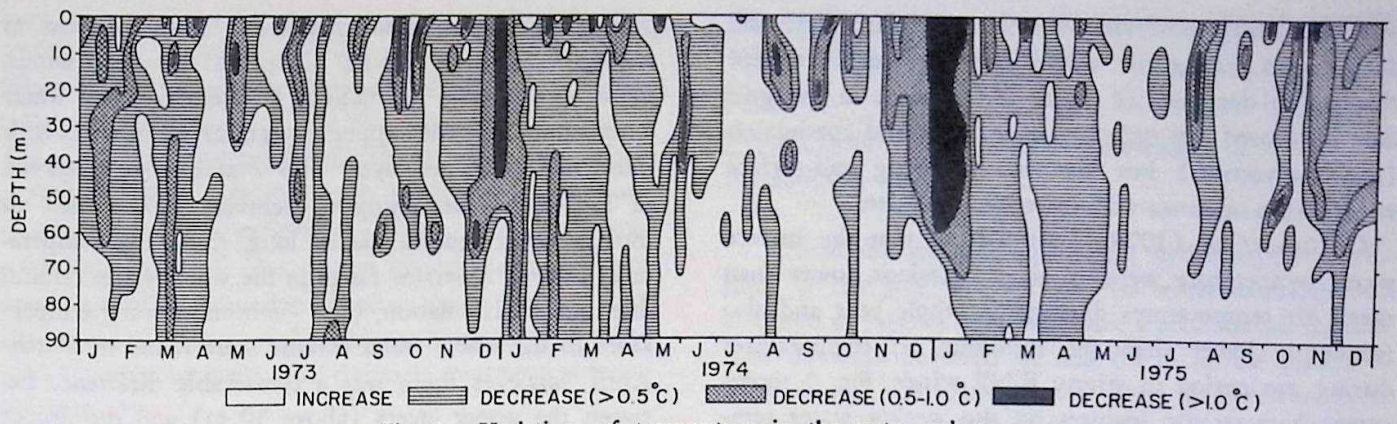


Fig. 2. Variations of temperature in the water column.

(1975), in comparison with the annual evaporation in the order of 2,530 mm (1972) and 2,720 mm (1975). These records clearly indicate that the area of the Gulf of Cariaco has a climate, characteristic of an arid region. In general, high precipitation was observed from August to November (December) corresponding to the period of low evaporation. Maximum values of daily average speeds of wind showed a range from 6.8 m/s in May (1974) to 7.4 m/s in April (1972) and May (1973) with a prevailing wind direction from NNE-ENE. Despite the fact that wind speeds showed remarkable fluctuations in rise and fall in each period, there was a definite periodic variation of wind speed and direction *i. e.,* a period of strong E-NE winds from December (January) to June (July) and a period of weak winds with a southerly component from August to November (December). Winds with a westerly component were registered only occasionally (approximately less than 20 days per year) in the period of weak winds. It may be concluded synoptically that the period of weak winds corresponds to the period of relatively high values of air temperature, low evaporation and high precipitation, while the period of strong winds coincides with a relatively low air temperature, high evaporation and very low precipitation.

As a consequence of the above mentioned meteorological conditions, the hydrographic and chemical characteristics of the Gulf of Cariaco also showed a clear existence of two markedly defined periods, *i. e.,* a period of water stagnation (with weak winds from the SW-SE) and a period of upwelling and water renewal (with strong winds from the E-NE).

During the period of water stagnation (weak wind intensity), a marked thermocline develops in the layers between 40 and 60 m, which impedes vertical mixing of water layers above and below the thermocline. The development of such a thermocline leads to the formation of an anoxic environment with a marked accumulation of nutrients (phosphate and ammonium) in the waters below the thermocline. In the waters above the thermocline, there was a continuous depletion of nutrients by photosynthetic activity and an increase of waters temperature and dissolved oxygen.

During the period of strong winds and upwelling, the outflow of the surface waters was generated by wind stress with the upward movement of the deep water at the eastern end of the gulf, following the penetration of subsurface waters from the Cariaco Basin. With the onset of strong winds from the east northeast, the pronounced thermocline that was formed during the period of water stagnation disappears as a result of intensive water circulation resulting in a very weak stratification of hydrochemical parameters. As a consequence of all these processes, the displacement of the nutrient-rich deep waters to the surface layers significantly contributed to enriche the fertility of the waters of the gulf.

Characteristic Variations of Water Temperature

Fig. 2 shows the seasonal variations in decrease and increase of temperature in the water column, which were obtained by calculating the difference between two successive observations. An appreciable decrease in water temperature was mostly found in the months from December to Abpril (May), which corresponded to the period of strong E-NE winds, while in the period of weak winds, there was a tendency in the increase of water temperature. However, these temperature changes

were frequently observed even in the intermediate and deep layers during the whole year. But such frequent changes in decreases of water temperature in the gulf may be caused not only by evaporation and conduction (and convection) but also by inflowing sub-surface waters from open sea with lower temperature.

OKUDA *et al.* (1978a) pointed out that the surface water tempereture were, in most occasions, lower than mean air temperatures during the whole year and also frequently lower than the minimun air temperatures during the period of strong E-NE winds. Fig. 3 shows some characteristic features on the weekly water temperature variation. And they may be summarized as follows; (i) Even during the period of weak winds, there were notable fluctuations in rise and fall of water temperature in the upper layers, as compared with those in the deeper layers (ii) - as may be observed in Fig. 3, the beginning of February 1974, when an intense water renewal lasted long, the water temperatures showed a narrow range in the whole water calumn due to rapid circulation, (iii) - minimum water temperature in the whole water column were found in March-April, however there was a remarkable difference between the upper layers (above 50 m) and the deeper

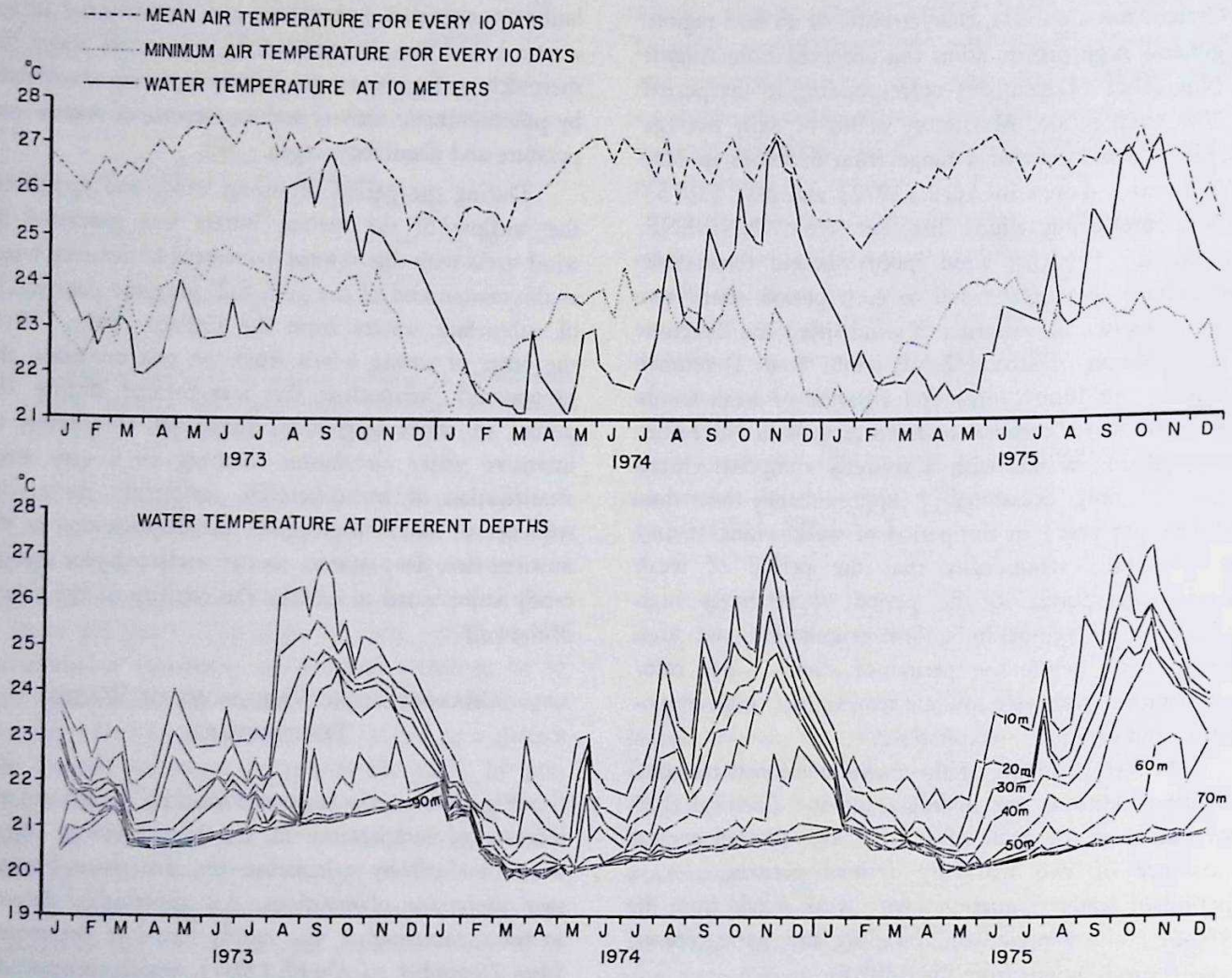


Fig. 3. Seasonal variations of mean and minimun air temperature (for every 10 days) and water temperature at different depths (with interval of 10 m).

layers (below 70 m) on the maximum water temperatures, *i, e.,* these values were observed in the upper layers in November or October, while in the deeper layers they continue to rise till January or February. After reaching the maximum values, the temperatures started to fall suddenly in both layers. Such variations indicated that the continuous inflow of the external water was initiated first in the upper layers and later was followed by the deeper water renewal. (iv) - during the period of strong winds, water temperatures at 10 m were found to be lower than the daily minimum air temperature.

In Fig. 3, water temperatures at a depth of 10 m are shown to compare them with mean and minimum air-temperatures, since the surface water temperatures are affected remarkably by heating of solar energy and also by heat exchange in the air-sea interface.

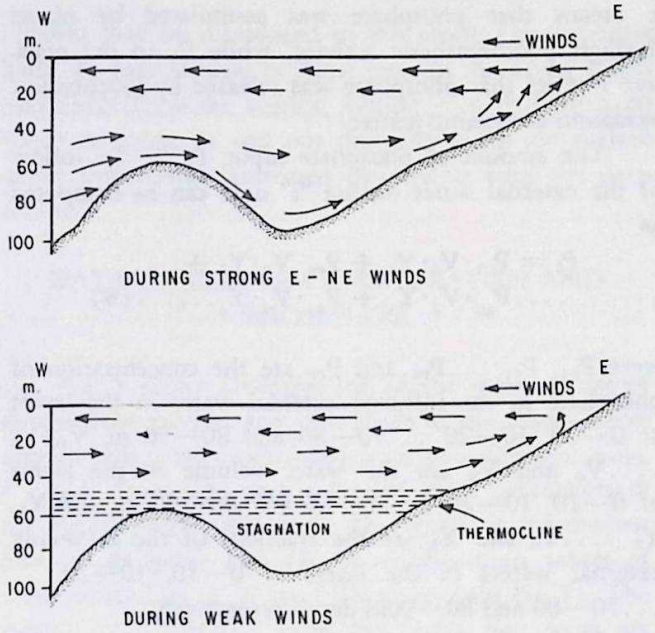


Fig. 4. Schematic illustration of water renewal.

For the surface heating, GADE (1961b) suggested that if the net incoming heat reached as much as 200 cal/cm^2/day, the temperature of water entering the gulf (1.55×10^9 m^3/day) may increase up to an order of 0,8 °C. Thus, surface heating in the gulf is considerably high. In the course of a relatively short period, an appreciable fluctuation in rise and fall of the water temperature at different depths of the gluf (except surface temperature) may be chiefly due to the surface heating and the inflow of the external waters with a low temperature.

Estimation of the Water Renwal and Phosphate Input

From the meteorological and hydrographic conditions of the gulf, a model on the water exchange was designed as follows (Fig. 4). Since a pronounced thermocline develops between 40 and 60 m in the period of weak winds, the waters below the thermocline were stagnated because of the very restricted water exchange with the Cariaco Basin. Therefore, when the winds are from a direction favorable for surface outflow, even if they are of low intensity, water exchange may occur within the upper layers above the thermocline. In the period of strong winds, the thermocline disappears as a result of intense water exchange which enhance the outflow of surface water from the gulf and the inflow of the sub-surface waters from the Cariaco Basin to the intermediate and deeper layers of the gulf. Also, this water exchange of the deeper layers depends not only on the intensity and direction of wind but on the prevailing density gradients.

If there is an active water exchange, it is reasonable to assume that the decrease of water temperature in the gulf is caused mainly by the inflow of the external waters with low temperature, so that the surface waters which have been affected by solar radiation and atmospheric exchange flowout. Thus, the rate of mixing between the internal and external waters may be estimated from the changes in the water temperature, so that the fraction of each water type in the mixture is a linear function of temperature.

Therefore, in order to estimate the rate of inflowing external water, it is basically assumed that the decrease of water temperature during a short period between two successive observations means the net inflow of the external water and the increase of water temperature implies that there is no occurrence of the inflow of the external water.

Fraction of the internal and external waters in the mixture:

The temperature of the mixture of the internal and external waters during a relatively short period of "t" days can be expressed using the following relation:

$$T_t = T_o \cdot X + T_e \cdot Y \quad \ldots\ldots (1)$$

where

T_o ..... the average initial temperature of the internal water,

T_t ..... the average water temperature after "t" days.

T_e ..... the average temperature of the inflowing external water during "t" days.

X ..... the fraction of the internal water in the mixture after "t" days, and

Y ..... the fraction of the inflowing external water in the mixture after "t" days.

Then, the fractions of the internal water, X, and the inflowing external water, Y, in the mixture during "t" days can be expressed as follows:

$$X = \frac{T_t - T_e}{T_o - T_e} \ldots (2) \quad \text{and} \quad Y = \frac{T_o - T_t}{T_o - T_e} \ldots (3)$$

It may be considered that the inflow of the external water into the gulf occurs under the following relation of temperature among 3 water types:

$$T_o > T_t > T_e$$

Volume of the inflowing external water into the gulf:

The volume of external water which flows during "t" days can be calculated as fallows:

$$V = V_1 Y_1 + V_2 \cdot Y_2 + \ldots\ldots V_8 \cdot Y_8 + V_9 \cdot Y_9 \ldots\ldots (4)$$

where V_1, $V_2 \ldots V_8$ and V_9 are the water volumes in the layers of 0—10, 10—20, ...70—80 and 80—90 m, and Y_1, $Y_2 \ldots\ldots Y_8$ and Y_9 are the fractions of the inflowing external waters in the layers of 0—10, 10—20, ...70—80 and 80—90 m respectively.

Phosphate input into the gulf:

The phosphate content, P_t, that results from the mixture of internal and external waters after "t" days can be computed as.

$$P_t = P_o \cdot X + P_e \cdot Y - P_b \ldots\ldots (5)$$

where P_o is initial phosphate content, P_e, phosphate content of the inflowing external water and P_b, amount of phosphate assimilated (or released) in the biological processes, then P_e, can be expressed as

$$P_e = \frac{P_t - P_o \cdot X + P_b}{Y} \quad \ldots\ldots (6)$$

Pb may be estimated from the following relation based on the change in the oxygen concentration that is involved during the photosynthetic process (oxygen production) and respiratory decomposition of organic matter (oxygen consumption).

$$P_b = \{O_t - (O_o \cdot X + O_e \cdot Y)\}/276 \ldots\ldots (7)$$

were O_t is the oxygen concentration of the mixture of the internal and external waters after "t" days, O_o, the initial oxygen concentration in the internal water, O_e, the oxygen concentration in the inflowing external water, and 276, the elemental ratio of change, by atoms between oxygen and phosphates. If, P_b is positive, then it means that phosphate was assimilated by plants through photosynthetic activity, while P_b in the negative implies that phosphate was released by biochemical oxidation of organic matter.

The amount of phosphate input, P_i, by the inflow of the external water during "t" days can be computed as

$$P_i = P_{e1} \cdot V_1 \cdot Y_1 + P_{e2} \cdot V_2 \cdot Y_2 + \ldots\ldots$$
$$\ldots\ldots P_{e8} \cdot V_8 \cdot Y_8 + P_{9e} \cdot V_9 \cdot Y_9 \ldots\ldots (8)$$

were P_{e1}, $P_{e2} \ldots P_{e8}$ and P_{e9} are the concentration of phosphate in the influxed external water in the layers of 0—10, 10—20 ...70—80 and 80—90 m, V_1, V_2 ....V_8 and V_9 are the water volume in the layers of 0—10, 10—20 ...70—80 and 80—90 m, and Y_1, Y_2 ....Y_8 and Y_9 are the fractions of the inflowing external waters in the layers of 0—10, 10—20, ...70—80 and 80—90m depth respectively.

For estimation of water renewal in this study, it was assumed that the water temperature at 10 m may represent an average water temperature of the surface layer (0—10 m), ignoring the surface temperature (0 m), in order to avoid any appreciable influence by heat exchange in the air-sea interface.

It must, however, be borne in mind that rates of water renewal obtained in this paper may be somewhat an under or overestimate for the following reasons: when the rate of inflow of external water is extremely high in the period of strong winds (or extremaly low in the period of weak winds) compared with the rate of water heating, an underestimate of the rates of water

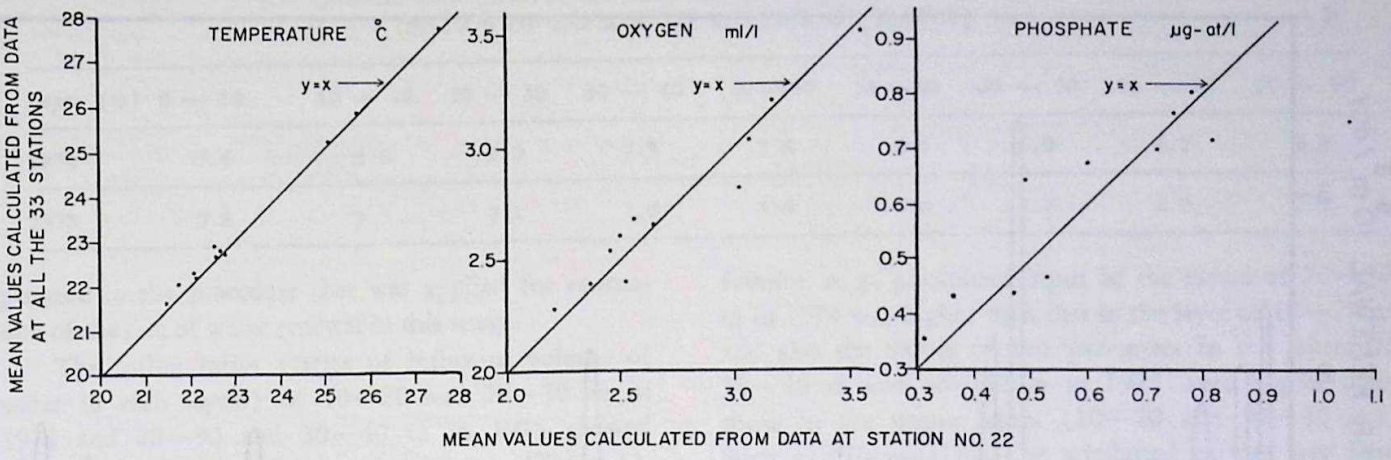


Fig. 5. Comparison between the mean values of temperature, oxygen and phosphate in the whole water column of the Gulf of Cariaco, calculated from the data at Sta. 22 and those calculated from the data at all 33 stations.

renewal may be introduced to the result. On the other hand, an overestimate of these rates in the upper layers may result from the vertical mixing even if there is no water exchange in and out the gulf, since the surface water temperature decreased by mixing with the deep waters.

DATA OF TEMPERATURE, OXYGEN AND PHOSPHATE

Fig. 5 shows a comparison of the mean values of temperature, oxygen and phosphate in the whole water column which were calculated from two different ways, *i. e.*, (i) from the mean values of these parameters in the water column at Station 22 (which is the deepest part of the gulf) and (ii) from the mean values of these parameters in all the 33 Stations (see Fig 1). The mean values obtained from the above two ways are distributed without great deviation from the line that denotes an equal value of the two mean values. Therefore, for this study, the rate of water renewal and phosphate input into the gulf were estimated using only the data of weekly observations on temperature, oxygen and phosphate at station 22 during 1974 and 1975 by applying the above mentioned procedure.

RATE OF WATER RENEWAL

The rate of water renewal varied considerably with the wind regime, which ranged from 0 to 3.41 $\times 10^9$ m^3 / day (Fig. 6). Highest rate of water renewal was observed toward the end of May, 1974 when strong NE winds blew consistently. The annual average rate of influx was 0.67×10^9 m^3 / day in 1974 and 0.52×10^9 m^3 / day in 1975 respectively, while 1.08×10^9 m^3 /day (1974) and 0.69×10^9 m^3 / day (1975 were estimated for the average rate of influx in the first half semester, which corresponded to the period of active water renewal. It was noted that even in the period of weak winds,, there was occurrence of appreciable water renewal in the gulf.

Measurements of the vertical current profile with a Ekman current meter in the period of strong winds was carried out by GADE (1961b). These results indicated a typical situation of outflux in the upper 20 m, with influx below 30 m, and the flushing period of the gulf was estimated to be 20 days. The same author reported that the total outflux (or influx) of water above (or below) the inflection level was estimated to be 1.55×10^9 m^3 / day.

The total annual inflow of external water into the gulf was estimated to be approximately 245×10^9 m^3 in 1974 and 188×10^9 m^3 in 1975, which correspond roughly 8 to 6 times respectively as much as the total volume of the gulf (Fig. 7). Such appreciable difference in the influx of external water into the gulf betwen 1974 and 1975, must have been caused by the different wind conditions in the 2 years.

In Fig. 7, the horizontal lines crossing the cumulative curves of the influx were indicated in order to

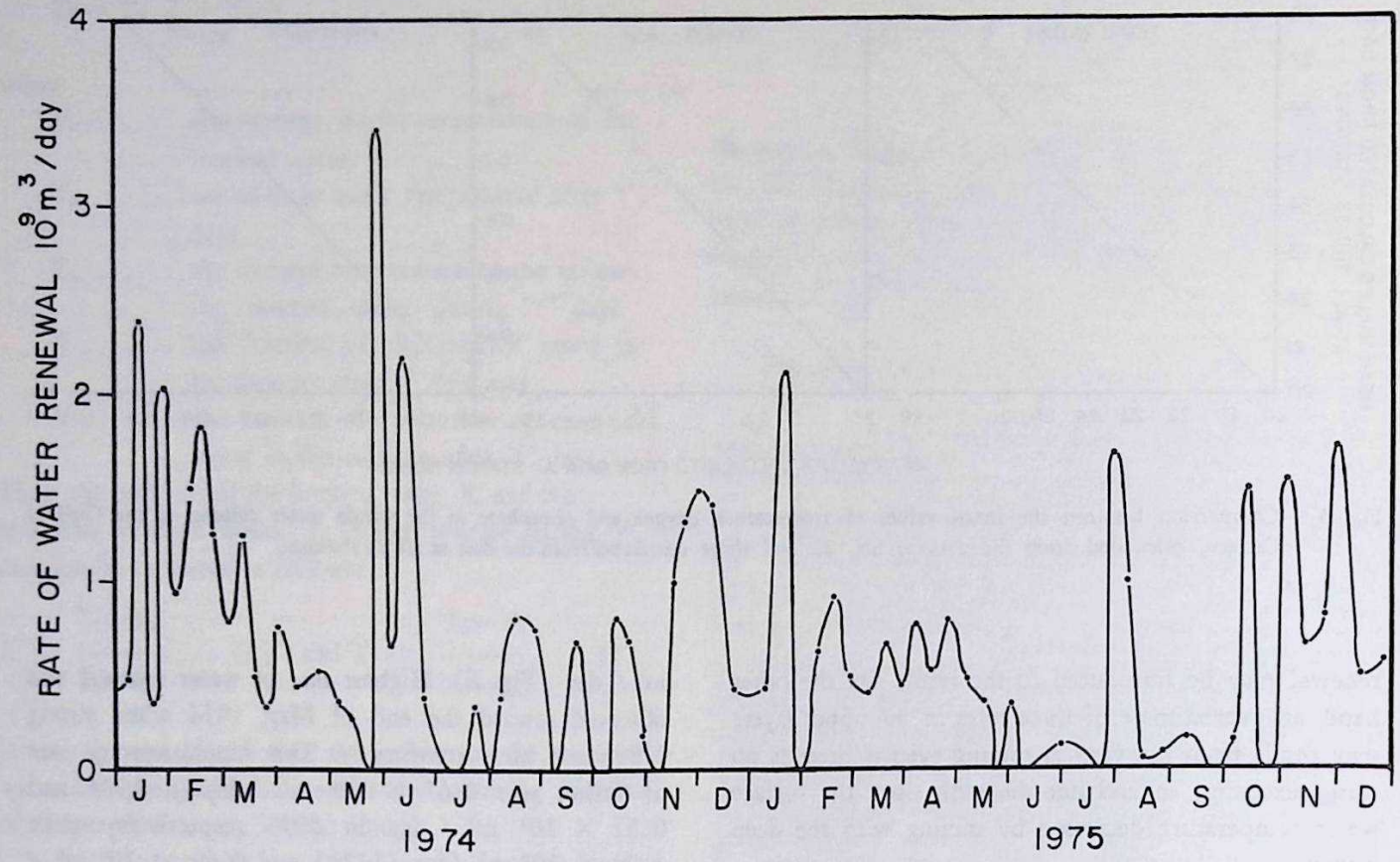


Fig. 6. Seasonal variation in the rate of water renewal.

show the influx which is equivalent to the total water volume of the gulf. As will be seen in Fig. 7, flushing was completed in approximately 21 days February of 1974, which was the shortest lapse (period of strong wind) and 111 days from June through October of 1975, which was the longest lapse (period of week winds). The expression of flushing in this case meant that cumulative volume of inflowing water corresponds to the equivalent amount of the total water volume of the gulf. Flushing period in February, 1974 reported in the present study almost was found to be the same with that obtained for January, 1962 by GADE (1961b).

In order to estimate the rate of water renewal in this study, it was assumed that the water exchange in the gulf resulted in the outflow of the gulf water in the upper layers and the inflow of external waters into the gulf in the intermediate and deep layers. However, fing. 8 shows a high influx of external water in the upper layers (0—10 and 10—20 m depth). Such an unexpected condition may arise from the fact that with the onset of strong winds, the deep water of the gulf with lower temperature are shifted to the surface by upwelling, with the result that this upwelled deep water outflows. Therefore, this volume of outflow of upwelled water in the upper layers has apparently the same volume of inflow of external water with lower tem-

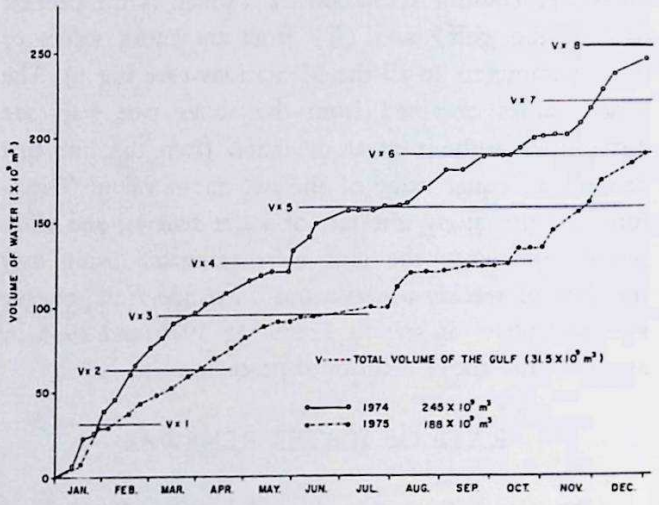


Fig. 7. Cumulative representation of the influx of external water into the gulf.

TABLA 1. — VERTICAL DISTRIBUTION OF INFLUX RATIO
(RATIOS OF INFLUX TO VOLUME OF WATER)

Layer (m)	0 — 10	10 — 20	20 — 30	30 — 40	40 — 50	50 — 60	60 — 70	70 — 80	80 — 90
1974	7.6	8.6	9.0	7.3	7.8	6.5	6.0	6.7	6.8
1975	5.8	5.3	7.1	7.0	5.6	5.6	5.7	3.8	3.1

perature in the procedure that was applied for estimation of the rate of water renewal in this study.

The influx ratios (ratios of influx to volume of water in each layers) of 10—20 and 20—30 m in 1974 and 20—30 and 30—40 m in 1975 showed much higher values in the water column. (Table 1). This may indicate that the influx of external water in these layers was comparatively more active than that in the other layers.

PHOSPHATE INPUT

The annual input of phosphate-P was estimated to be about 3,350 tons in 1974 an 2,510 tons in 1975. (Fig. 8).

Vertical distribution of phosphate input presents considerably a different pattern from that of influx of external water, *i. e.*, the latter in each layer tends to decrease from the surface to the bottom layer, on the contrary, the former does not show the same fashion, *e. g.*, phosphate input in the layers of 20—30 m in 1974 was higher than that in the layer of 10—20 m and also the values of this parameter in the layers of 30—40 m and 40—50 m in 1975 were higher than those in the upper layers (10—20 and 30—30 m). Such a difference may be attributed to the fact that the phosphate input depends, to a great extent, on the size of water renewal but the concentration of phosphate in the inflowing external water is also an important factor.

The monthly variations of the influxe of external water and the phosphate input showed almost the same fluctuation, *i e.*, higher values of the both parameters during the period of strong winds and lawer ones in the period of weak winds (Fig. 9). However, it is of interest to observe in Fig. 9 that the phosphate input in October (1974), November and December (1974 and 1975) showed strikingly low values in spite of considerably hig influx in these months. This may have been caused by the fact that in these months, corresponding to the beginning of water renewal, the water exchange was limited to the upper layers and the phosphate con-

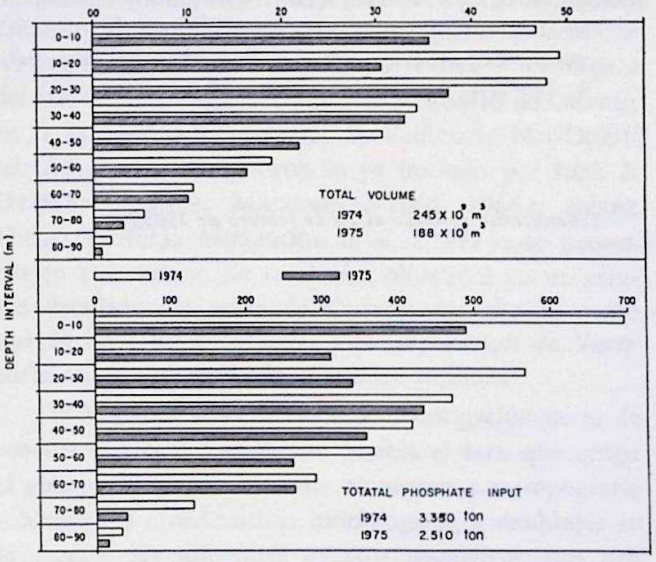


Fig. 8. Vertical distribution of the influx of external water and phosphate input into the Gulf of Cariaco.

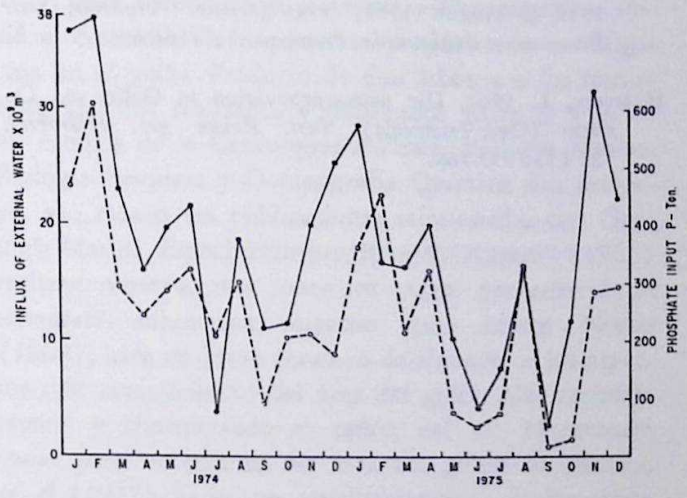


Fig. 9. Seasonal variations in the influx of external water and phospate input into the Gulf of Cariaco.

centration of inflowing waters were still not high, because these waters penetrated from the relatively shallower upper layers of the Cariaco Basin.

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